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Radionuclides: Background Information Document--Standard for Radon-222 Emissions from Underground Uranium Mines

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This report presents background data and other information on underground uranium mining and related emissions of radionuclides, the risks associated with these emissions, and methods for reducing the emissions. Information was complied from the technical literature, previous studies by EPA and the Bureau of Mines, comments received from rulemaking notices, and discussions with industry representatives.

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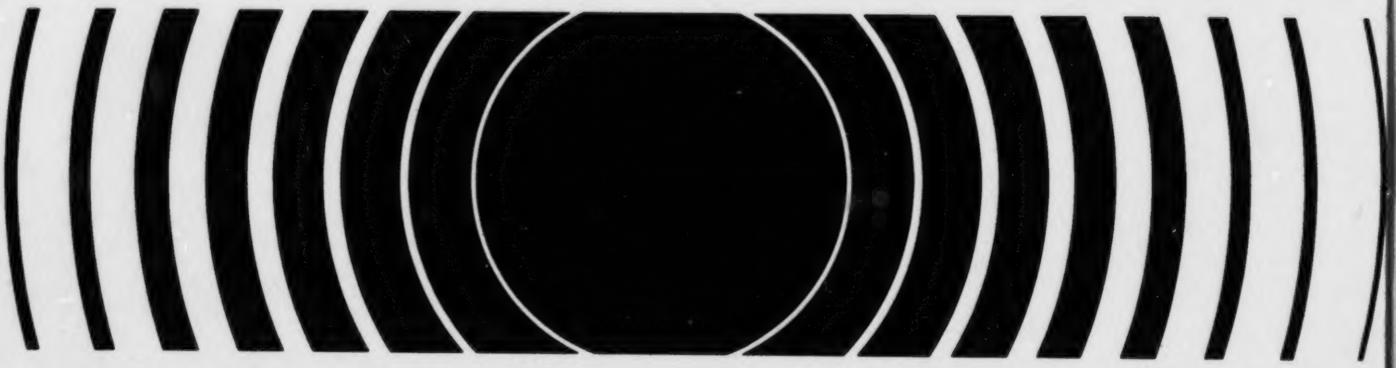

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RADIONUCLIDES

BACKGROUND INFORMATION DOCUMENT--
STANDARD FOR RADON-222 EMISSIONS
FROM UNDERGROUND URANIUM MINES

April 10, 1985

U.S. Environmental Protection Agency
Office of Radiation Programs
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Chapter 1: INTRODUCTION

1.1 History of Standard Development

In 1977, Congress amended the Clean Air Act (the Act) to address airborne emissions of radioactive materials. Before 1977, these emissions were either regulated under the Atomic Energy Act or unregulated. Section 122 of the Act requires the Administrator of the U.S. Environmental Protection Agency (EPA), after providing public notice and opportunity for public hearings (44 FR 21704, April 11, 1979) to determine whether emissions of radioactive pollutants cause or contribute to air pollution that may reasonably be expected to endanger public health. On December 27, 1979, EPA published a notice in the Federal Register listing radionuclides as hazardous air pollutants under Section 112 of the Act (44 FR 76738, December 27, 1979). To support this determination, EPA published a report entitled "Radiological Impact Caused By Emissions of Radionuclides into Air in the United States--Preliminary Report" (EPA 520/7-79-006, Office of Radiation Programs, U.S. EPA, Washington, D.C., August 1979).

On June 16, 1981, the Sierra Club filed suit in the U.S. District Court for the Northern District of California pursuant to the citizens' suit provision of the Act (Sierra Club v. Gorsuch, No. 81-2436 WTS). The suit alleged that EPA had a nondiscretionary duty to propose standards for radionuclides under Section 112 of the Act within 180 days after listing them. On September 30, 1982, the Court ordered EPA to publish proposed regulations establishing emission standards for radionuclides within 180 days of the date of that order.

On April 6, 1983, EPA published a notice in the Federal Register proposing standards for radionuclide emission sources in four categories: (1) Department of Energy (DOE) facilities, (2) Nuclear Regulatory Commission (NRC) -licensed facilities and non-DOE Federal facilities, (3) underground uranium mines, and (4) elemental phosphorus plants. Five additional categories of sources that emit radionuclides were identified, but it was determined that there were good reasons for not proposing standards for them. These included (1) coal-fired boilers; (2) the phosphate industry; (3) other extraction industries; (4) uranium fuel cycle facilities, uranium mill tailings, and management of high-level radioactive waste; and (5) low-energy accelerators (48 FR 15077, April 6, 1983). To support these proposed standards and determinations, EPA published a draft report entitled "Background Information Document, Proposed Standards for Radionuclides" (EPA 520/1-83-001, Office of Radiation Programs, U.S. EPA, Washington, D.C., March 1983).

On February 17, 1984, the Sierra Club filed suit to compel final action in the U.S. District Court for the Northern District of California, pursuant to the citizens' suit provision of the Act (Sierra Club v. Ruckelshaus, No. 84-0656 WHO). On July 25, 1984, the Court granted Sierra Club's summary judgment motion and ordered EPA to promulgate standards or to make a finding that radionuclides are not a hazardous air pollutant within 90 days of the date of the order.

On October 23, 1984, EPA withdrew its proposed standards for radionuclide emissions from the following categories: (1) elemental phosphorus plants; (2) DOE facilities; (3) NRC-licensed facilities and non-DOE Federal facilities; and (4) underground uranium mines. The Agency also affirmed its original decision not to regulate emissions from the five other source categories considered (49 FR 43906, October 31, 1984). The proposed standards for the first three categories were withdrawn because the Administrator determined that current practice provides an ample margin of safety in protecting the public health from the hazards associated with exposure to radionuclides from these sources.

In the case of underground uranium mines, the Administrator withdrew the proposed standard because it did not meet the legal requirements of Section 112 of the Clean Air Act. Simultaneous with this action, EPA published an Advance Notice of Proposed Rulemaking for radon-222 emissions from underground uranium mines. The purpose of this was to solicit additional information on control methods such as bulkheading and other forms of operational controls for radon-222 that would meet the legal requirements of Section 112 (49 FR 43915, October 31, 1984). At the same time, EPA also published an Advance Notice of Proposed Rulemaking for radon-222 emissions from operating uranium mills (49 FR 43916, October 31, 1984).

On October 31, 1984, the U.S. District Court, Northern District of California, issued an order requiring the Administrator and the Agency to show cause why they should not be held in contempt of the Court's July 25 order. A Court hearing was held on November 21, 1984, to consider the issue. In a ruling on December 11, 1984, the Court found the Administrator and the Agency in contempt and ordered the following remedial action:

1. (a) Issue within 30 days of the date of the order final radionuclide emission standards for DOE facilities, NRC-licensed and non-DOE Federal facilities, and elemental phosphorus plants, and

(b) Issue within 120 days of the date of the order final radionuclide emission standards for uranium mines; or

2. Make a finding based on the information presented at hearings during the rulemaking, that radionuclides are clearly not a hazardous pollutant.

On December 21, 1984, EPA requested a stay of the District Court's order; this request was denied on January 3, 1985. The Agency subsequently requested a stay from the 9th Circuit Court of Appeals on January 8, 1985. This request also was denied; however, the Court did allow the Agency an additional 7 days to provide time for further appeal to the U.S. Supreme Court. These efforts also failed. Therefore, to comply with the District Court's order, EPA promulgated standards for radionuclide emissions to air from DOE facilities, NRC-licensed and non-DOE Federal facilities, and elemental phosphorus plants (50 FR 5190). Litigation regarding these three standards is continuing.

In February 1985, EPA announced a proposed work practice standard to limit radon-222 emissions from underground uranium mines (50 FR 7280, February 21, 1985). The proposed standard was based on bulkheading mined-out and temporarily inactive mine areas to reduce the amount of radon-222 emitted to the atmosphere.

Following publication of the proposed standard, EPA conducted an informal public hearing in Albuquerque, New Mexico, on February 27 and 28, 1985, and the public record was held open until March 28, 1985, to allow written comments to be received. The EPA has now considered all written and oral comments; responses to these comments are discussed in the *Federal Register* notice announcing the final rule.

1.2 Purpose and Scope of This Background Information Document

> This ~~document~~ Report presents background data and other information on underground uranium mining and related emissions of radionuclides, the risks associated with these emissions, and methods for reducing the emissions. Information was compiled from the technical literature, previous studies by EPA and the Bureau of Mines, comments received from rulemaking notices, and discussions with industry representatives. <

1.3 Other Regulatory Factors

The Department of Labor's Mine Safety and Health Administration (MSHA) has established limits on exposures to radon decay products for mine workers. The current standard limits annual exposure to 4 WLM (Working Level Months) and prohibits exposure to concentrations greater than 1.0 WL (Working Level) in any active area unless approved respirators are worn (30 CFR 57).

Chapter 2: INDUSTRY DESCRIPTION

2.1 Overview

The uranium mining industry in the United States was originally established at the end of World War II in response to a large government military program, and this initial demand for uranium resulted in extensive exploration for uranium and the development of the uranium extraction industry.

In the United States, large ore deposits are located in parts of western Colorado, eastern Utah, northeastern Arizona, northwestern New Mexico, Wyoming, and Texas (NRC80). The majority of the uranium deposits are sandstone deposits. Ore deposits generally occur in layers that lie nearly parallel to the host beds. Ore bodies are generally irregular in shape and size, ranging from small masses measuring only a few meters in width and length to masses tens of meters thick, hundreds of meters wide, and thousands of meters long. The volumes of the ore bodies range from a few hundred to several million tons. The extreme variation of uranium ore bodies with regard to size, shape, depth, continuity, physical properties, geologic structure, grade, and groundwater condition results in each underground uranium mine being somewhat different in its layout and mining method. Furthermore, the configuration of a specific underground uranium mine changes continuously as the operation progresses.

Currently, the three techniques for mining uranium are open-pit mining, in situ leaching, and underground mining. Underground mining is the principal method for recovery of uranium ores lying more than 150 meters (500 ft) below the surface. Considerable expense is involved in excavation; therefore, development of the mine is governed by the geometry of the ore body as a function of ore grade. Development of an underground mine proceeds by the blasting and/or excavation of a wall face. Mine ventilation is necessary to provide fresh air to the miners to keep the radon-222 decay product concentrations in conformance with MSHA regulatory requirements (see Section 1.3). Usually, no effort is made to control radon-222 emissions from mine wall surfaces by the use of coatings or to remove radon-222 from the air by physical or chemical means. Some effort is expended, however, to confine high concentrations of radon-222 in the worked-out inactive portions of mines by sealing off or bulkheading that section (NRC80). It is frequently necessary to exhaust air from the sealed-off portion of the mine to the surface to maintain a slight negative pressure relative to the active working areas. Maintaining this slight negative pressure minimizes leakage of contaminated air into the active mine areas.

2.2 Process Description

The choice between underground and open-pit mining is primarily one of economics. Several factors influence the economics, such as the ratio of machine costs to labor costs, ore cut-off grade, and depth of the ore body.

2.2.1 Underground Uranium Mining

Underground uranium mining is usually carried out by a modified room and pillar method. A schematic of a hypothetical underground shaft mine is shown in Figure 2-1. The sequential activities in the development of such a mine are listed below and described in the following subsections.

- Main shaft sinking
- Haulage drifting
- Ventilation shaft sinking
- Long-hole exploration
- Raising to a stope level
- Stope development
- Stope extraction

Some mines follow the ore vein, and access to the vein is gained via an incline or declined drift instead of a shaft.

Main Shaft Sinking

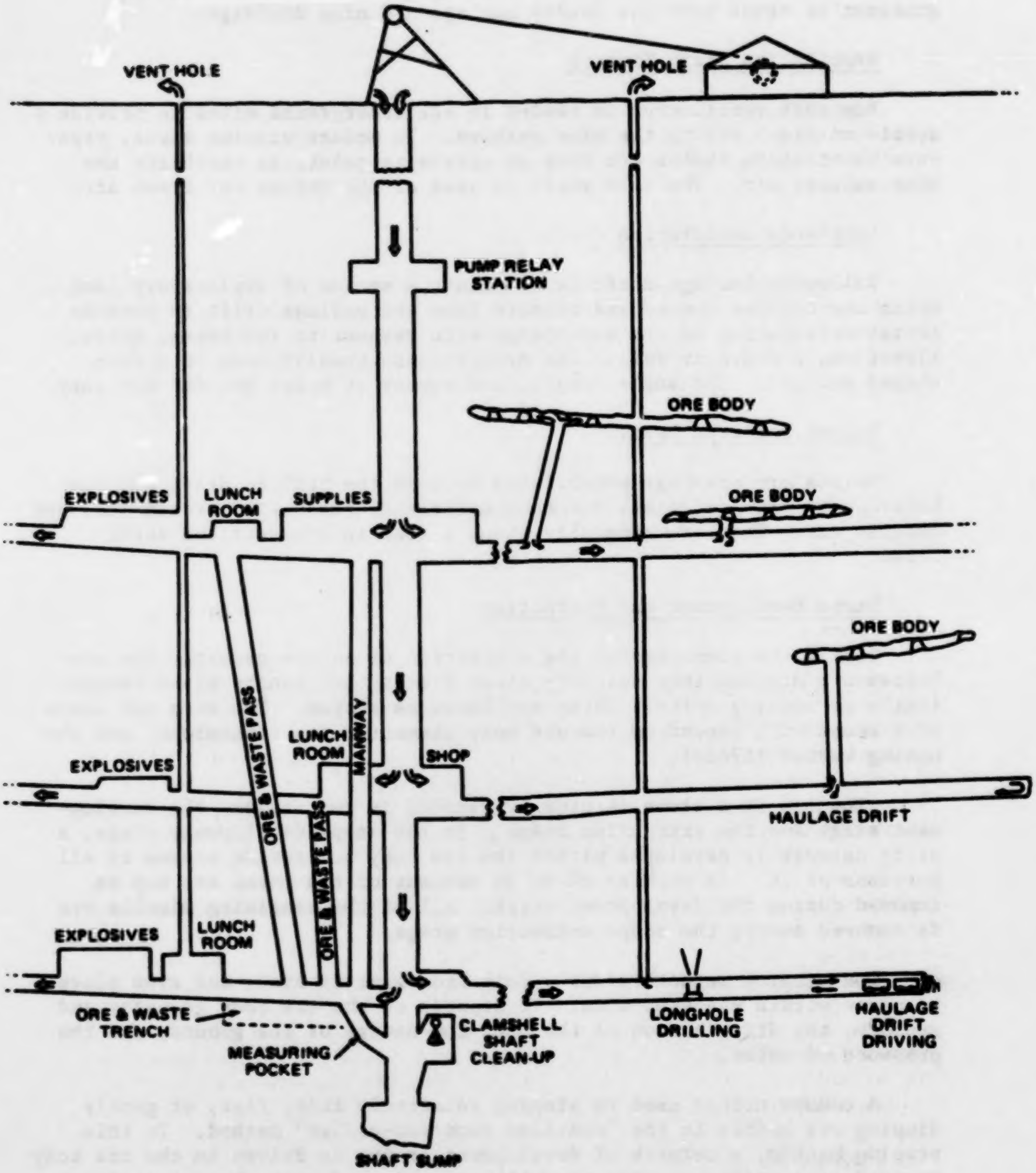
Depending on depth and geologic conditions, either vertical or inclined shafts may be used to access the ore. As deeper deposits are developed, however, the trend is toward the use of vertical shafts. These range in depth from a few hundred feet to the present-day maximum of about 900 meters (3,000 feet).

Modern production shafts are circular and concrete-lined. Inside diameters range from 3 to 5 meters (10 to 16 feet), depending on production requirements. Ore and waste ore are hoisted in two skips operating in balance. Utility lines (electric cables, water lines, and compressed air pipes) are attached to the shaft wall.

The main or production shaft generally extends 30 meters (100 feet) or more below the production level to accommodate spillage cleanup and sump capacity. Normally, it is located outside the ore perimeter or horizon (EPA80).

Haulage Drifts

Following the construction of the main shaft, haulage drifts are extended out below the anticipated ore horizons. They are usually driven


VENT HOLE
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PUMP RELAY STATION
ORE BODY
EXPLOSIVES
LUNCH ROOM
SUPPLIES
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ORE & WASTE PASS
MANWAY
LUNCH ROOM
SHOP
EXPLOSIVES
HAULAGE DRIFT
ORE & WASTE PASS
EXPLOSIVES
LUNCH ROOM
ORE & WASTE TRENCH
MEASURING POCKET
CLAMSHELL SHAFT CLEAN-UP
LONGHOLE DRILLING
HAULAGE DRIFT DRIVING
SHAFT SUMP

Figure 2-1. Schematic diagram of an underground uranium mine (EPA80).

about 2.5 meters by 2.7 meters (8 feet by 9 feet), with a 1 percent gradient to favor both the loaded haulage and mine drainage.

Ventilation Shaft Sinking

Adequate ventilation is needed in all underground mines to provide a supply of fresh air to the mine workers. In modern uranium mines, separate ventilation shafts are sunk at strategic points to ventilate the mine exhaust air. The main shaft is used as the intake for fresh air.

Long-Hole Exploration

Following haulage drift development, a series of exploratory long holes are drilled upward and outward from the haulage drift to provide better delineation of the ore bodies with respect to thickness. grade, elevation, and dip or roll. The drilling is normally done in a fan-shaped pattern. The angle, depth, and number of holes per fan may vary.

Raises to Stope Level

Raises are openings established between the haulage drift and ore horizons to provide access for men, materials, fresh air, broken ore, and exhaust air. They are generally about 4 feet in diameter and steel-lined.

Stope Development and Extraction

During the planning for the extraction of an ore deposit, the ore bodies are divided into suitably sized blocks that can be mined conveniently as working units. These are known as stopes. The size and shape of a stope will depend on the ore body geometry, its dimensions, and the mining method (EPA80).

The ore in a stope is usually removed in two stages, the development stage and the extraction stage. In the stope development stage, a drift network is developed within the ore body to provide access to all portions of it. As much as 30 to 35 percent of the total ore may be removed during the development stage. All of the remaining minable ore is removed during the stope extraction stage.

The stoping method varies widely from mine to mine, and even place to place within the same mine. It depends on the ore body geometry and geology, the distribution of the ore, the nature of the ground, and the presence of water.

A common method used in stoping relatively thin, flat, or gently dipping ore bodies is the "modified room-and-pillar" method. In this stoping method, a network of development drifts is driven in the ore body to produce a series of pillars, which are mined during the extraction stage. Normally the drifts are 2 meters by 2 meters (6 feet by 6 feet) and the pillars 12 meters by 12 meters (40 feet by 40 feet). When the drift network has been completed, the stope is ready for extraction;

however, a developed stope sometimes may not be extracted until 6 months or even a year later. The extraction usually begins from the farthest end of the mine and proceeds toward the ore pass. As the pillars are removed, the roof is sometimes allowed to cave in if the area is not below the water table. Sometimes pillars of low-grade ore may be left behind to control subsidence.

2.2.2 Ore Handling

Ore extraction involves drilling out a blasting round, loading the explosives, and blasting, in that order. In shaft type mines, the resulting loose ore is moved to the nearest stope exit, where it is hauled along development drifts to vertical raises and gravity-fed to the haulage way. From there, it is transported to the main shaft for hoisting to the surface. In single ore horizon mines, ore is hauled out at the same elevation as the ore body. The haulage may be a part of the worked-out ore area. The ore is maintained in a stockpile near the mine surface. It is then usually transported to the mill and blended (Ja80 and Br84).

2.2.3 Ventilation Techniques

Adequate ventilation is needed in all underground mining to supply fresh air to the mine and to flush out contaminated air. In underground uranium mining, the need for adequate ventilation is even more critical for the dilution and removal of mine air contaminated with radon-222 and its decay products. The layout and mining plan of each underground uranium mine is unique; therefore, each ventilation system is also unique (EPA80).

In general, a parallel ventilation system is preferred to a series system because air residence time and mine resistance to air flow are less. Other ventilation systems that could be used include a blowing system, an exhaust system, or a combination of the two (push-pull) (Ja80).

The ventilation system usually consists of a primary system and several secondary systems. The primary system includes the main intake airway, fresh airways, exhaust air drifts, and an exhaust ventilation shaft. Fans are used on either the intake shaft or the exhaust shaft. Positive-pressure ventilation is created in the primary system by using forced-draft fans at the ground surface, and negative pressure is created by using exhaust fans. The production shaft and haulage drifts are commonly used as fresh-air intakes and airways. A large mine may have more than one shaft for fresh-air intake and a combination of forced-draft and exhaust fans at different vent shafts (EPA80).

Adequate ventilation typically requires about one vent hole for each 28,300 cubic meters (million cubic feet) of active mine volume. The ventilation air requirements vary from mine to mine. In a recent Battelle study of 13 mines, total mine ventilation ranged from 75 to 330 m^3/s (158,000 to 706,000 ft^3/min) (B184).

A secondary system, sometimes called "booster" or "auxiliary" system, consists of fans and vent tubing to redirect portions of the primary air supply to specific working areas that are not on the main ventilation system. These systems utilize small fans (5-25 HP), which usually push air to the working areas through flexible tubing.

In newer mines, exhaust air from working areas contaminated with radon-222 is collected into exhaust drifts and routed directly to the exhaust shaft. In older mines, however, radon-222-contaminated air from a working area is often discharged into the next working area or into the primary air system. In older mines that operate under positive ventilation, exhaust air is usually allowed to escape by a convenient route, which might be the main access shaft. Modern practice in underground uranium mining, however, dictates that radon-222-contaminated exhaust air be routed away through exhaust drifts that are separate from haulage drifts and shafts. More and more mines are exercising great care to separate exhaust airways and are taking steps to prevent exhaust air from contaminating the fresh air supply (EPA80).

Vent holes can exit the ground in either a horizontal or vertical position (see Figure 2-2). Previously, horizontal vent pipes were used to direct the moisture-laden gas stream away from the electrical equipment located near the vent. Cascading of the condensed water vapor and ice during colder months frequently damaged the equipment. The practice of lining the vent pipe with steel and providing piped weepholes to control water seepage has enabled vertical discharges to be used without damage to the equipment.

2.3 Economic Profile of the Underground Mining Industry

An overview of the underground uranium mining industry is presented here. A more detailed profile of this industry was developed for EPA by Jack Faucett Associates (JF85).

2.3.1 Domestic Uranium Production

The uranium industry has changed substantially since its beginning in the 1940's. Prior to the mid-1960's, the Federal Government owned a significant amount of the uranium in the United States, and military use was virtually the only source of demand for uranium (DOE84c). During the 1960's, however, the commercial nuclear power industry began to emerge as a result of the passage of the Private Ownership of Special Nuclear Materials Act, Public Law 88-489, 1964. At the same time, the Government began to withdraw from the market and meet its uranium requirements from its own stockpiles. Thus, the uranium industry entered a transitional period in which commercial nuclear powerplants became the dominant souce of demand and the Government moved from its historical position as sole buyer and, in fact, made a complete exit from the market (DOE84a).

In 1966, under provisions of the Atomic Energy Act, the Atomic Energy Commission put into effect a complete embargo of foreign uranium for domestic use. The purpose of this law was to ensure the development

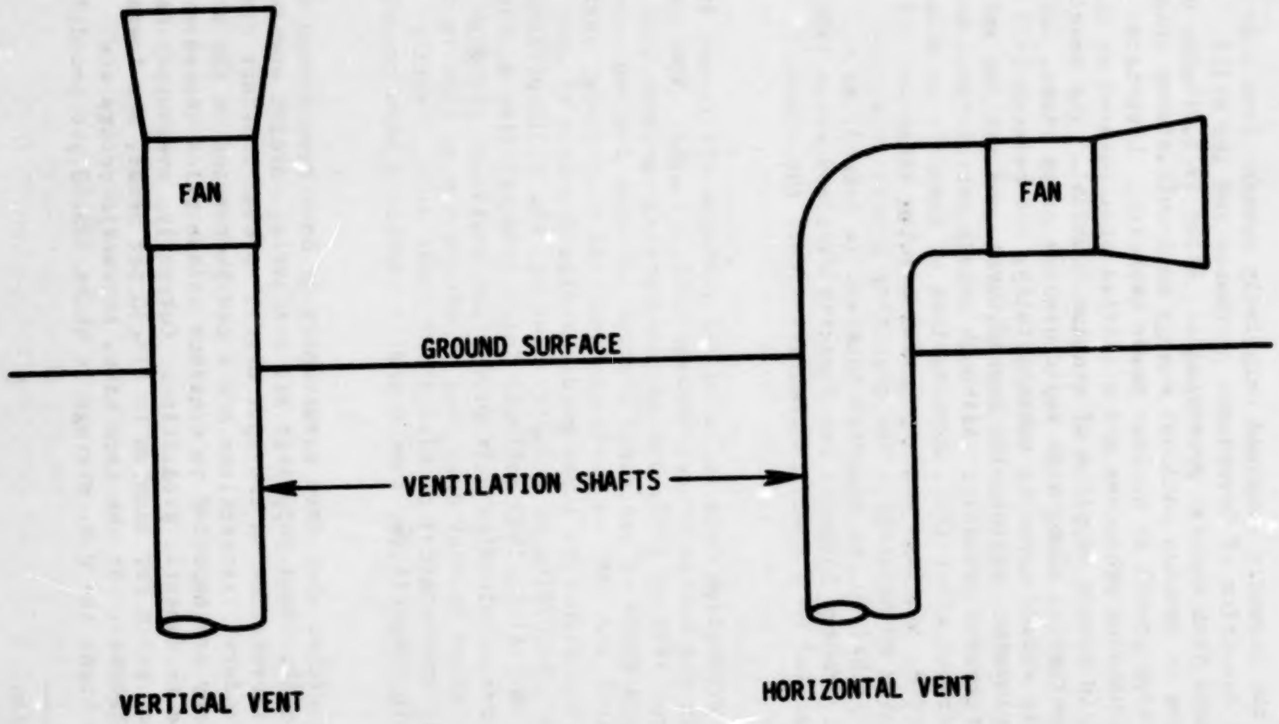
FAN
FAN
GROUND SURFACE
VENTILATION SHAFTS
VERTICAL VENT
HORIZONTAL VENT

Figure 2-2. Examples of vertical and horizontal exhaust vents.

of a domestic uranium industry with sufficient capacity to meet domestic uranium requirements. The restriction was designed to encourage growth in a period of low prices, limited demand, growing imports, and high expectations of future demand.

Nevertheless, the industry remained relatively dormant from 1966 to 1975 because of the cessation of Government purchases and the still limited uranium demand from nuclear powerplants. After 1975, rising oil prices and the desire to develop national energy self-sufficiency created expectations of a large growth in nuclear power capacity. Long-term contract agreements between producers and utilities proliferated as utilities sought to obtain secure supplies of uranium (DOE83a). The development of long-term contracts, along with rapid uranium price rises, led domestic producers to expand capacity substantially, and between 1975 and 1980 production, employment, exploration expenditures, and milling and mining investment increased steadily. Although import restrictions underwent phased withdrawal after 1977, expectations of domestic producers remained high. By 1980, 34 firms were operating uranium mines and 147 were engaged in uranium exploration. The resulting growth in supply capability was not matched by the expected increase in demand; as a result, the domestic uranium industry has steadily declined since 1980. The excess supply has led to a sharp contraction within the domestic production industry.

The historical production data in Table 2-1 indicate the trends in uranium production in the United States between 1966 and 1983. Tonnage increased sharply from 1975 to 1980, but declined steeply between 1980 and 1983. The average grade of processed uranium ore also dropped substantially between 1966 and 1982 as producers depleted high-grade, easily obtainable reserves and turned to lower-grade uranium deposits to meet contract obligations. According to industry sources, the 0.012 percent rise in ore grade from 1981 to 1983 reflects "high-grading" (the mining of only high-grade ores to minimize unit production costs).* Although high-grading enables mines to stay open now, it shortens mine life in the long run by making it uneconomical to mine lower-grade ores. Despite such efforts to remain competitive, some domestic suppliers have ceased production.

Many mines have either shut down permanently or have been placed on standby (see Appendix A). Some suppliers are purchasing foreign uranium and utility uranium inventories on the spot market to meet contract commitments. Such "secondary" transactions are a new phenomenon in the uranium industry, but they are expected to continue unless price increases encourage an increase in domestic production. Currently, oversupply has driven the spot market price for uranium to $15.50 per pound, its lowest point since 1973 (NUEXCO84). At the same time, production costs are estimated to be at a high; the U.S. average is about $35.00 per pound.**

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* Industry information.

** Spot market prices are estimates of the price at which transactions for immediate delivery of uranium could be concluded. Contract prices are price agreements for future deliveries of uranium.

Table 2-1. Historical trends in U.S. uranium production by uranium mills and other sources (DOE84a, DOE80-83)

Year	Short tons of U_3O_8	Grade of ore (% U_3O_8)
1966	10,589	0.229
1967	11,253	0.203
1968	12,368	0.195
1969	11,609	0.208
1970	12,905	0.202
1971	12,273	0.205
1972	12,900	0.213
1973	13,235	0.208
1974	11,528	0.176
1975	11,600	0.170
1976	12,747	0.157
1977	14,939	0.154
1978	18,486	0.131
1979	18,736	0.105
1980	21,852	0.119
1981	19,237	0.114
1982	13,434	0.121
1983	10,579	0.126

As a result of this situation, domestic production, once a growing and profitable segment of the economy, has fallen victim to declining demand and competition from foreign sources. The number of domestic production sources (including open-pit mines, underground mines, and other sources) fell from a peak of 432 in 1979 to only 135 in 1983. The decline continued in 1984, and as of November 1984, only 26 underground mines and 14 open-pit mines were operating.

The decline in employment in all areas of the U.S. uranium industry since 1979 is evident in the data shown in Table 2-2. Exploration employment has dropped the most dramatically; the 1983 employment was less than 10 percent of that in 1979. In 1983, milling employment (which is closely tied to uranium mining) was less than one-half 1979 employment and mining employment was about 25 percent. The tremendous drop in exploration employment illustrates producer expectations of little need for capacity expansion, whereas the declines in mining and milling reflect the large number of shutdowns and closures. Since 1978 the total labor force has been reduced by about 75 percent, or 16,000 workers.

Table 2-2. Employment in the U.S. uranium industry, 1979-1983
(DOE80-83, 83b)
[person-years[a]]

	Year				
	1979	1980	1981	1982	1983
Mining					
Underground	5,706	5,037	3,518	2,150	1,109
Open-pit	3,782	3,414	1,857	1,365	755
In situ/byproduct	1,704	1,530	1,536	1,185	929
Other	3,267	3,317	2,098	1,679	930
Subtotal mining	14,459	13,298	9,009	6,379	3,723
Milling	3,236	3,251	2,367	1,956	1,518
Exploration	4,066	3,370	2,300	769	374
Total	21,761	19,919	13,676	9,104	5,615

(a)Includes technical and supervisory employees.

The decline in capital expenditures since 1979 has also been dramatic. In 1983, total industry capital expenditures were only $67 million, compared with $801 million in 1979 (current dollars). Mining and milling investment ($30 million) was at a 10-year low as a result of the current excess capacity within the industry. In the absence of a turnaround in market conditions, the low levels of expenditure are likely to persist (see Table 2-3).

A number of negative forces have combined to cause the current state of the industry. Perhaps the most important of these is that the growth

Table 2-3. Capital expenditures in the U.S. uranium industry (DOE83b)
(millions of current dollars)

	Exploration		Mining		Milling		Total
Year	Expenditures	Number of companies	Expenditures	Number of companies	Expenditures	Number of companies	Expenditures
Actual							
1979	316	164	282	26	203	26	801
1980	267	147	273	34	242	27	782
1981	145	107	212	29	59	22	416
1982	74	86	81	23	11	15	166
1983	37	77	27	17	3	14	67

in electricity generated by nuclear plants and the expansion of nuclear power capacity have been much slower than was forecasted in the mid-1970's, partially because of numerous construction delays and cancellations. At the end of 1983, 80 nuclear reactors (see Table 2-4) were licensed to operate in the United States, totaling 64.4 gigawatts of generating capacity (DOE84b). The long lead times associated with the ordering, constructing, and permitting of nuclear powerplants make it extremely unlikely that any additional orders for new nuclear plants will add to operable capacity before 1996. Furthermore, 10 of the 58 plants in the construction stage as of December 31, 1983, were cancelled in the first 10 months of 1984.

Table 2-4. Status of U.S. nuclear powerplants as of December 31, 1983 (DOE84b)

Status	Number of reactors	Net design capacity (MWe)
Operable		
In commercial operation	76	60,200[a]
In power ascension	4	4,200
Subtotal	80	64,400
In construction pipeline		
In low-power testing	3	3,400
Under construction		
More than 50 percent complete	37	40,400
30 to 50 percent complete	4	4,600
Less than 30 percent complete	2	2,400
Indefinitely deferred	10	11,700
Reactors on order	2	2,200
Subtotal	58	64,700
TOTAL	138	129,100

[a] Includes Three Mile Island 1 (819 MWe), which has an operating license but is in an extended shutdown mode. Three Mile Island 2 and Dresden 1 are not included.

Imports currently play a major role in the U.S. uranium market. The import restrictions in effect from 1964 to 1977 underwent a phased withdrawal, and as of 1984, no import limitations were imposed.* The result has been a steady increase in uranium imports from nations possessing high-grade (and thus low-cost) uranium deposits. In 1977, only 4.7 percent of the uranium delivered to DOE enrichment plants by domestic utilities was of foreign origin; whereas in 1983, foreign sources provided 16.9 percent of total deliveries (DOE84a). A growing portion of utility requirements are expected to be supplied by foreign-origin uranium during the second half of this decade.

A third factor contributing to the current downturn in the uranium industry is the large inventory levels held by both producers and utilities. Utilities, anticipating a growing need for uranium, entered into long-term contracts to purchase large amounts of domestically-produced uranium. As actual needs fell short of expected needs because of nuclear powerplant construction delays and cancellations, large inventories began to accumulate. These inventory supplies, currently estimated to cover utility requirements for four to five years, adversely affect suppliers in two ways. First, they may extend the downturn in uranium demand for several years by decreasing the need for utilities to enter into new contracts. Second, high interest rates have increased inventory holding costs; thus, some utilities are contributing to the current excess supply by offering inventory stocks for sale on the spot market.

2.3.2 The Underground Uranium Mining Industry

As noted in the previous section, domestic uranium is produced by a number of different mining techniques. Conventional mining, either open-pit or underground, has historically accounted for over 90 percent of U.S. production; however, in recent years, in situ leaching, heap leaching, and copper byproduct methods have become increasingly important. In 1983, the conventional mining share of production fell to an estimated 70 percent.** Domestic production by type of mining method for the years 1979 to 1983 is presented in Table 2-5.

Underground mines, historically the leading source of domestic production, accounted for an estimated 39 percent of domestic production in 1983. Appendix A lists the underground mines in operation or closed as of October 1984 (DOL84). Although production data from individual mines are not available, employment at each mine is reported and provides some indication of the level of mining activity at the 26 mines in operation at that time. The number still in operation in March 1985 had fallen to six, which are located in four states: two in Arizona, two in Colorado, one in New Mexico, and one in Utah. These six mines are identified in Appendix A.

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[*] As of January 1985, there were no bills pending in either the U.S. House of Representatives or the U.S. Senate that would reimpose import restrictions.

[**] Unofficial DOE estimate.

Table 2-5. Uranium production by mining method (DOE80-83)

	Underground		Open pit		Other[a]	
Year	1000 tons	Percent of total	1000 tons	Percent of total	1000 tons	Percent of total
1979	6.3	30	9.4	45	5.0	25
1980	9.6	41	10.4	45	3.3	14
1981	8.6	43	7.0	36	4.1	21
1982	6.2	46	3.9	29	3.3	25
1983[b]	5.2	42	4.1	33	3.1	25

Note: The production totals in this table are not strictly comparable with those in Table 2-1 because the underground and open-pit production represents the production in ore before mill processing, while the production in Table 2-1 represents uranium obtained from ore, as reported by mills.

[a] Includes production from solution mining, byproduct, heap leaching, mine water, and low-grade stockpiles.

[b] Figures for 1983 are EPA calculations based on unofficial DOE estimates (DOE84d).

Key statistics of underground uranium mining are presented in Table 2-6. Between 1979 and 1983, the number of operating underground mines dropped from 300 to 95, and employment fell from 5706 to 1109 person-years. Although U_3O_8 production and raw ore production are both down, raw ore production showed a larger decrease because of a rise in average ore grade. The average ore grade of underground mine production has nearly doubled since 1979 because of the shutdown of low-grade mines and high-grading practices at operating mines.

2.3.3 Forecasts of Domestic Production

Annual forecasts of the total production of U_3O_8 from domestic sources for 1985 through 1990 are presented in this section. The forecasts are based on the results of the low electricity demand case of the DOE viability study (DOE84c); however, adjustments were made to reflect the most likely level of imports, rather than the severely constrained import scenarios of that study. The share of total unfilled delivery requirements to be supplied by domestic producers is projected by assuming a 37.5 percent import share through 1990. Also unlike the DOE study, total unfilled requirements for delivery to the DOE enrichment facility are projected under the assumption that the enrichment facility will continue operation at the current level of efficiency of U-235 recovery. Total demand from domestic sources is then calculated as the sum of current domestic contracts for delivery of domestically produced U_3O_8, the assumed domestic share of total unfilled delivery requirements, and current export contract commitments. The results of this analysis indicate that total domestic production of U_3O_8 is expected to fall from 10,000 tons in 1984 to 7600 tons in 1990.

Virtually all uranium produced by U.S. mine operators is consumed by one sector, the nuclear power industry. Therefore, forecasts of domestic production depend largely on the long-term status of this industry. The requirements of nuclear powerplants currently in operation may be considered a well-established, baseline demand; thus, uranium needs of operating powerplants may be projected with high precision. Forecasts of requirements of nuclear powerplants currently under construction are highly speculative, however. Our base-case analysis assumes that no plants currently less than 30 percent complete will be on line before 1990. This and other assumptions used in this analysis are equivalent to those used for the low electricity demand case in the DOE analysis. In addition to the uncertainty surrounding the demand for enriched uranium for the nuclear power industry, several other factors complicate the forecast of domestic demand for uranium ore. Small changes in the efficiency of operation of the DOE enrichment facility* can lead to large

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*The operating efficiency of the enrichment facility is determined by assaying the concentration of U-235 in the tailings discarded after enrichment. The facility currently operates at a tails assay level of 0.25 percent. A lower tails assay level indicates recovery of a greater percent of the U-235 originally present in the input feed, and hence, greater efficiency of enrichment.

Table 2-6. Underground uranium mining statistics (DOE80-83)

Year	Ore delivered to mills (1000 tons)	U_3O_8 production (1000 tons)	Average grade (%)	% of total U_3O_8 production	Number of mines	Employment (person -years)
1979	5356	6.3	0.118	30	300	5706
1980	6351	9.6	0.151	41	303	5037
1981	5229	8.6	0.164	43	167	3518
1982	2809	6.2	0.224	46	139	2150
1983	NA(a)	5.2(b)	NA	42(b)	95(c)	1109
1984	NA	NA	NA	NA	26(d)	NA

(a) NA = not available.

(b) 1983 production calculated from unofficial DOE estimates (DOE84d).

(c) 1983 number of mines represents an unofficial DOE estimate.

(d) Operating underground mines as of November 1984 (DOL84).

changes in required U_3O_8 deliveries for enrichment. The likelihood of a change in the operating efficiency of the enrichment facility depends on a second uncertain factor--the continued availability of cheap imported ore from Canada, Australia, and South Africa. If imports were to be curtailed by Government action intended to protect the domestic uranium mining and milling industries, this could lead to a significant rise in the price of U_3O_8 delivered to the enrichment facility and shift the optimal tails assay level downward. The lower tails assay level would be desirable, as it would reduce the amount of U_3O_8 required for delivery. The magnitude of this effect can be quite substantial.

In the absence of import constraints, the import share of total unfilled requirements is expected to rise because of the significantly lower price of the imports. In total, imports now account for more than 30 percent of uranium deliveries. The requirements for uranium import commitment dependency under Public Law 97-415 make it unlikely that the import share will be permitted to rise significantly above today's level. If the projected import share should rise to 37.5 percent, the law requires that the U.S. International Trade Commission initiate an investigation under Section 201 of the 1974 Trade Act (19 U.S.C. 2251). It is unlikely that imports in excess of 37.5 percent will be permitted. For this analysis, the import share of unfilled delivery requirements is assumed to peak at 37.5 percent and remain at this level. Under this import assumption, unfilled delivery requirements from domestic sources are projected to rise to a level of 3300 tons U_3O_8 per year by 1989, which yields cumulative unfilled requirements from domestic sources of 9200 tons U_3O_8 by 1990.

The projected level of domestic demand in the base case is below the production potential of currently existing mines that have low cost reserves. Therefore, it is unlikely that any new underground mines will be opened during the remainder of this decade.

Domestic requirements may be filled by production from underground mines, open-pit mines, or from several other sources including solution mining, byproduct production, heap leaching, mine-water recovery, and low-grade stockpiles. In Table 2-7, production by each source is indexed to the most recent peak production level, which occurred in 1980 for underground and open-pit mines, and in 1979 for other sources. In recent years, underground mining has suffered a reversal in its market share trend, which peaked in 1982. This loss of market share will be accelerated by the most recently-announced closing of the Kerr-McGee mines, which produced 1100 tons of U_3O_8 in 1983. In the projections, this downward trend is continued, with underground mining accounting for only 30 percent of domestic production by 1990. The projections for open-pit mining are based on a slight increase in market share, but declining production over the remainder of the decade. Other sources are forecasted to remain roughly constant at present production levels despite the decreasing demand, which leads to a slightly rising market share. The projections contained in Table 2-7 are highly speculative and are based simply on extrapolations of recent trends.

Table 2-7. Historic and projected U_3O_8 production (U_3O_8 in ore), market share, and capacity utilization index by source

	Underground			Open-pit			Other sources			Total production	
Year	Annual[a]	Market share[b]	Index[c]	Annual	Market share	Index	Annual	Market share	Index	Annual	Index
Historic											
1979	6.3	30	0.66	9.4	45	0.90	5.0	25	1.00	20.7	0.89
1980	9.6	41	1.00	10.4	45	1.00	3.3	14	0.66	23.3	1.00
1981	8.6	43	0.90	7.0	36	0.67	4.1	21	0.82	19.7	0.85
1982	6.2	46	0.65	3.9	29	0.38	3.3	25	0.66	13.4	0.58
1983[d]	5.2	42	0.54	4.1	33	0.39	3.1	25	0.62	12.4	0.53
Projected											
1984	3.9	39	0.41	3.1	31	0.30	3.0	30	0.60	10.0	0.43
1985	3.1	33	0.32	3.2	34	0.31	3.2	34	0.64	9.5	0.41
1986	3.0	32	0.31	3.2	34	0.31	3.2	34	0.64	9.4	0.40
1987	2.9	32	0.30	3.1	34	0.30	3.1	34	0.62	9.1	0.39
1988	3.0	32	0.31	3.2	34	0.31	3.2	34	0.64	9.4	0.40
1989	2.8	31	0.29	3.0	34	0.29	3.1	35	0.62	8.9	0.38
1990	2.3	30	0.24	2.6	34	0.25	2.7	36	0.54	7.6	0.33

[a] Annual U_3O_8 production (thousand tons).
[b] Percent of U_3O_8 total production.
[c] Ratio of current production to peak year production.
[d] Figures for 1983 are EPA calculations based on unofficial DOE estimates (DOE84d).

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Chapter 3: ATMOSPHERIC EMISSION OF RADON-222

3.1 Theoretical Considerations

3.1.1 Origin and Generation of Radon-222

Uranium ore contains both uranium and the decay products of uranium. In nature, uranium is about 99.3 percent uranium-238. Therefore, it is the decay products of uranium-238, shown in Figure 3-1, that govern the radioactive content of the ore and the production of radon-222 (NRC81). This figure also shows the half-life and the principal decay mode of each radionuclide.

As Figure 3-1 indicates, radium-226 is the parent of radon-222, which is the only member of the decay chain that is a gas. Furthermore, radon-222 is a noble gas; therefore, it does not usually combine with other elements to form nongaseous compounds. As a gas, radon-222 can be released to the atmosphere if it escapes the mineral matrix that contains its parent, radium-226.

Almost all natural soils contain some uranium-238, which ultimately decays to radon-222. When uranium ore lies undisturbed underground, only a very small fraction (if any) of the radon-222 it produces escapes to the atmosphere. Radon-222 has a half-life of only 3.8 days; therefore, most radon-222 that is generated more than a few meters below the surface decays into nongaseous radionuclides before it can migrate through the soil and escape into the atmosphere. When uranium ore is mined, however, the constant exposure of previously undisturbed uranium ore allows radon-222 to escape into the mine atmosphere.

Underground uranium mines have ventilation shafts installed at appropriate distances along the ore deposit. A large mine will usually have several ventilation shafts; some mines have as many as 14 vents. Mine ventilation is necessary to reduce concentrations of radon-222 and radon-222 decay products in the mine air to which miners are exposed. Such ventilation is usually provided by high-capacity (up to 200,000 cfm) exhaust fans that remove air from the mine through the ventilation shafts and discharge it at or just above ground level. All radon-222 released from underground mine surfaces will either be contained in the ventilation exhaust or it will decay in underground airways because of stagnation. Radon-222 also can be released by the ore and subore stockpiles on the surface and by small amounts of waste that are brought to the surface and accumulated during the life of the mine (EPA84).

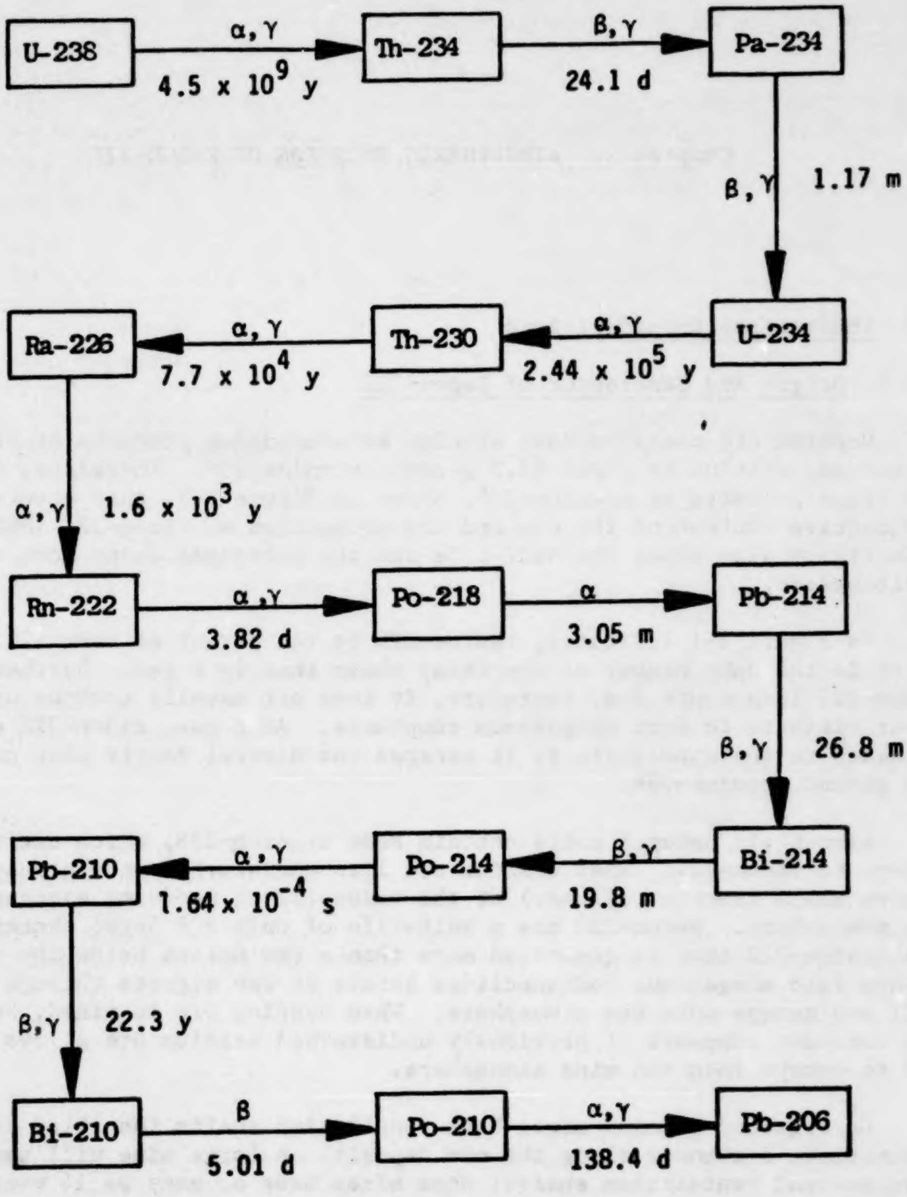
U-238
α, γ
4.5 x 10^9 y
Th-234
β, γ
24.1 d
Pa-234
β, γ
1.17 m
U-234
α, γ
2.44 x 10^5 y
Th-230
α, γ
7.7 x 10^4 y
Ra-226
α, γ
1.6 x 10^3 y
Rn-222
α, γ
3.82 d
Po-218
α
3.05 m
Pb-214
β, γ
26.8 m
Bi-214
β, γ
19.8 m
Po-214
α, γ
1.64 x 10^-4 s
Pb-210
β, γ
22.3 y
Bi-210
β
5.01 d
Po-210
α, γ
138.4 d
Pb-206

Figure 3-1. Uranium-238 decay chain

3.1.2 Factors Affecting Emissions of Radon-222 to Air

Radon-222 emissions from ventilation exhausts, although highly variable, are directly related to the amount of radon-222 emanated within the mine. The volume of ventilation air exhausted from an individual mine is not believed to have a significant effect on total radon-222 emissions. Although the concentration (pCi/liter) of radon-222 may vary as a function of exhaust volume, the total amount discharged is much more dependent on radon-222 emanation within the mine.

A number of interrelated factors affect the rate and/or amount of radon-222 emanation within the mine atmosphere. These include ore grade, mining practices, production rate, age of the mine, size of active working area, and several other variables.

Mining practices (e.g., rate of advance and size of broken ore) also influence the rate of radon-222 emanation. About 5 percent of the available radon-222 in the rock is released at the instant of blasting (Th74). Thus, the more frequently blasting occurs, which would be indicative of a rapid advance in the mining area, the greater the release rate of available radon-222. Radon-222 emanation from broken ore increases with greater fragmentation of the ore. Overblasting that opens cracks extending farther into the ore zone further increases radon-222 emanation from the fractured rock.

Measurement programs at underground mines (Ja79 and Ja80) indicate that the amount of radon-222 exhausted with ventilation air is more directly related to the total surface area of underground workings being ventilated than to daily production rates. The total underground surface area is generally proportional to the total cumulative amount of ore extracted during the lifetime of the mine. This is logical because the uranium content of the rock surface in the mined-out areas of the mine is not zero; rather, it varies up to the economic cutoff grade for mining. The total area of exposed mine surfaces is many times that of a working face from which ore is being extracted, especially for a mine that has been in operation for several years. Therefore, radon-222 emission rates tend to increase with the age of the mine because more surface area has become exposed by subsequent mining.

3.1.3 Difficulties in Estimating Radon-222 Emissions

Conceptually, development of a "model underground mine" that could be used to predict or estimate annual radon-222 emissions as a function of some explanatory variable (e.g., ore grade, production rate) would be desirable. As discussed in the previous subsection, however, many known variables affect radon-222 emissions. One of the most important variables appears to be that of exposed mine surface area. Thus, instead of a "model underground mine," another method for estimating emissions would be to establish a relationship between mine surface area and amount of ore mined and then a further correlation between mine area exposed and radon-222 emitted. In principle, this approach appears feasible; in practice, however, it has not proven to be realistic because of a lack of information. The kind of information necessary to model exposed mine surface area and to estimate the lifetimes of current mines including when new mines will be opened is not currently available.

An alternative approach for estimating total radon-222 emissions is to measure radon-222 releases from enough operating mines and for long enough time periods so that the sample population represents a significant fraction of the total production of U_3O_8 from underground mines. Assuming the sample population is representative of the industry, an average emission factor can be calculated that relates radon-222 emission to U_3O_8 production. This is the approach that EPA has selected in forecasting total radon-222 emissions from underground mines. This approach and its limitations are discussed in the following subsections.

3.2 Radon-222 Emissions

3.2.1 Radon-222 Sources

Radon-222 emissions from underground uranium mines originate from aboveground sources or underground sources. Aboveground sources include waste piles, ore storage piles, and discharged mine water. Underground sources include radon-222 emanation from wall rock, groundwater, and broken ore. Radon-222 emissions from underground sources are released to the atmosphere through mine ventilation systems. In 1978 and 1979, the U.S Nuclear Regulatory Commission contracted Battelle/Pacific Northwest Laboratory (PNL) to quantify radon-222 emissions from underground uranium mines. In addition, Battelle/PNL investigated correlations between a mine's annual radon-222 emissions and specific mine characteristics (Ja79 and Ja80). The data base and correlations that Battelle/PNL established during this project currently comprise the bulk of EPA's radon-222 emission data.

3.2.2 Measured Emissions

The current EPA data base on radon-222 emissions from underground uranium mines consists of radon-222 emission measurements from 27 mines. This data base has a number of limitations. First, the emission measurements were made 7 and 8 years ago. Current emission rates have not been directly measured and therefore must be extrapolated from previous measurements. These estimates may not adequately reflect the effects of mine closures, production decreases, and changes in mining practices that have occurred since the measurements were made. Second, for estimation of current and future total annual emissions, EPA's data base must be assumed to be reasonably representative of the entire underground uranium mining industry. While this was probably true in 1978-1979, it is uncertain whether the 27 previous mines sampled are currently representative of mining with respect to mine age, cumulative ore produced, ore grades, and mining practices. A third limitation concerns calculating a mine's annual radon-222 emissions. Annual radon-222 emissions are calculated by extrapolating short-term sampling results over a 1-year period. This limitation may not be significant because continuous monitors were used to record radon-222 emissions for periods up to 1 month at four mine vent locations. Except for diurnal radon-222 emission peaks (usually 1.2 to

1.5 times the average emission, which corresponded to decreases in barometric pressure), individual mine vent emissions were found to be relatively constant.

The following discussion focuses on radon-222 emissions from underground sources (i.e., mine vent emissions). Mine vent radon-222 emissions greatly exceed the radon-222 emissions from all other sources. Battelle/PNL determined that aboveground emissions constitute only between 2 and 3 percent of a mine's total radon-222 emissions. The overall uncertainty of the total mine emission measurements is +30 to -18 percent (Ja80). Consequently, contributions from aboveground sources to total radon-222 emissions are insignificant when compared with the overall uncertainty in estimated total emissions.

For purposes of this document, mine vent radon-222 emissions are discussed and tabulated on three bases: 1) curies per year (Ci/y), 2) curies per short ton of U_3O_8 produced annually (Ci/ton U_3O_8), and 3) curies per year per short ton of cumulative ore produced (Ci/ton-y).

Table 3-1 summarizes radon-222 emission data from 27 underground uranium mines that were sampled by PNL in 1978-1979. The vent emissions listed in this table represent the sum of measured emissions from as many as 14 individual mine vents at some mines. Radon-222 emissions varied significantly among individual vents from a common mine ventilation system. Therefore, all vents from a common system were sampled simultaneously, and the radon-222 emissions were summed to obtain total mine vent emissions (Ja80).

The mine vent emissions presented in Table 3-1 do not necessarily represent the radon-222 emissions from completely uncontrolled mines. An undetermined (but probably significant) number of these underground uranium mines practiced some degree of bulkheading and backfilling during 1978 and 1979. This means that the measured emission rates already reflect some (unknown) level of radon-222 emission control. Although it is possible to calculate a theoretical effectiveness (see Section 6.3.3) of a bulkhead in reducing radon-222 emissions from a bulkheaded area, EPA cannot conclude that this theoretical radon-222 reduction efficiency can be applied to the measured radon-222 emissions because these emission rates do not represent uncontrolled baseline conditions.

The 27 uranium mines listed in Table 3-1 supplied 5760 out of the 9200 short tons of U_3O_8 produced from underground uranium mines during 1978. Consequently, this data set represents 63 percent of the underground uranium mining industry in 1978. Overall annual radon-222 emissions, calculated by summing the 27 individual mine vent emissions shown in Table 3-1, were estimated to be 150,000 Ci/y (Ja80). Assuming the 27 mines constituted a representative sample of all underground uranium mines operating at that time, total annual radon-222 emissions from mine vents in the underground uranium mining industry in 1978 are estimated to be 240,000 Ci/y.*

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*(9200/5760) x 150,000 ≈ 240,000.

Table 3-1. Summary of radon-222 emissions from underground mine vents (Ja80)

Mine identification	1979 measurement (Ci/y)	1978 measurement (Ci/y)	Average (Ci/y)
A	7,400		7,400
B	4,700	4,300	4,500
C	5,200	3,900	4,600
D	3,630		3,630
E	29,800		29,800
F	9,200	9,500	9,400
G	2,150	1,460	1,800
H	15,200		15,200
I	1,690		1,690
J	7,760	8,100	7,900
K	7,000	5,870	6,400
L	1,470	1,320	1,400
R	15,000	14,600	14,800
T	1,890		1,890
U	890		890
V	1,010		1,010
Y	17,500		17,500
Z		2,640	2,640
AA	2,100	1,490	1,800
BB	2,130	1,840	2,000
CC		2,120	2,120
DD		960	960
EE	6,500		6,500
FF	2,510		2,510
GG	190	146	170
HH	1,040		1,040
II	470		470
		Total for all mines	150,000

For purposes of relating mine vent radon-222 emissions to mining production, radon-222 was emitted from underground uranium mine vents at a rate of 26 Ci/ton of U_3O_8 mined.

Most of the emissions from underground uranium mines can be attributed to individual mines having a cumulative ore production of at least 100,000 short tons. Table 3-2 presents estimated average annual radon-222 emissions for 252 mines as a function of mine size (i.e., cumulative ore production). This table shows that the larger mines (about 25 percent of the total number of mines) contribute approximately 95 percent of the total radon-222 emissions.

Table 3-2. Mine size categories and percentages of the uranium industries radon-222 emissions[(a)] (B184)

Cumulative ore production (1,000 tons ore)	Number of mines	Percent of mines	Average emissions per mine (Ci/y)	Emissions per size category (%)
1,000 - 4,700	25	10	8,800	76
100 - 1,000	39	15	1,400	19
10 - 100	82	33	140	4
1 - 10	83	33	14	1
0.1 - 1	23	9	1.4	0
Totals	252	100		100

(a) Data on the number of mines and size categories are from the DOE, Grand Junction, Colorado, as of 1/1/79.

3.2.3 Relationship of Cumulative Ore Production to Radon-222 Emissions

Concurrent with measuring radon-222 emissions in 1978 and 1979, Battelle/PNL recorded mining production rates and other parameters related to mining operations (e.g., mine water discharge rates, number of mine vents, mine age). Correlations between radon-222 emissions and annual U_3O_8 production, mine age, mine surface area, cumulative ore production, and cumulative U_3O_8 production were investigated (Ja79 and Ja80). Battelle/PNL attempted to derive correlations between specific mining parameters and the mine's total annual radon-222 emission rate. Valid correlations would provide a method of predicting radon-222 emissions from individual mines and the entire underground uranium industry.

Of the parameters investigated, cumulative ore production appeared to be most directly correlated with radon-222 emissions. The cumulative ore production of a mine has a statistically significant linear relationship with its radon-222 emissions. Table 3-3 provides data showing the correlation between radon-222 emissions and cumulative ore production for 15 of the previously discussed 27 mines. These radon-222 emissions reflect both aboveground and underground sources. In most cases, total radon-222 emissions were estimated by multiplying the mine vent emissions by 1.025 (Ja80). Where possible, however, total emissions were calculated by using actual data obtained from mine operators. The cumulative ore production data were furnished by the mine operators. Figure 3-2, a graphical representation of Table 3-3, relates radon-222 emissions to cumulative ore production (Ja80). The line shown in Figure 3-2 was constrained to pass through the origin because it is reasonable to assume that radon-222 emissions begin concurrently with ore production. The slope of this line (i.e., 4.4×10^{-3} Ci/y per short ton of cumulative ore produced) is an emission rate factor representative of the data presented in Table 3-3. The two broken lines in Figure 3-2, with slopes of 0.57 (i.e., 0.44 + 0.13) and 0.31 (i.e., 0.44 - 0.13), establish the 95 percent confidence intervals relative to the presented data. Without including the origin as a point, the coefficient of determination (R^2) is 0.53. The R^2 value indicates that about one-half the variability can be accounted for by the relationship between radon-222 emissions and cumulative ore production (Ja80). Although the correlation is significant, it emphasizes the fact that radon-222 emissions are also a function of variables other than cumulative ore production. For example, positive-pressure ventilation, mine-water flow rates, bulkheading, backfilling, and barometric pressure also affect radon-222 emissions. The R^2 value may also be confounded by the use of various levels of control techniques (e.g., bulkheading and backfilling) by mine operators during the radon-222 emission test periods. The use of varying levels of bulkheads during the emission tests could account for some of the rather low values shown in Table 3-3. An effective model capable of accurately relating radon-222 emissions to mine characteristics has not been developed yet.

3.2.4 Estimated Future Emissions

The apparent relationship between curies of radon-222 emitted and cumulative tons of ore extracted from a mine provides a basis for approximating current and future emission rates. However, such a forecasting procedure (even with necessary assumptions specified) requires current mining information on each active mine and also requires knowledge of future mining trends. Necessary information includes the cumulative ore production figures for each mine or the current radon-222 emissions, mine age, mining practices, working days per year, expected active life of the mine, current production rates, and all anticipated changes that may affect each mine. By multiplying the emission rate factor of 4.4×10^{-3} Ci/ton-y by the forecasted ore production rates for each mine and adding the resulting value to the current emission rate of the mine, future

Table 3-3. Correlation between radon-222 emissions and cumulative ore production (Ja80)

Mine	Radon-222 emissions[(a)] (Ci/y)	Cumulative ore production through 1978[(b)] (10^6 tons)	Radon-222 emission rate per cumulative ore production (10^{-6} Ci/ton-y)
B	4,600	1.2	3,800
C	4,700	1.8	2,600
D	3,700	1.5	2,500
E(c)	30,000	3.9	7,700
F(c)	9,500	4.7	2,000
G(c)	2,000	0.45	4,400
H(c)	15,300	2.6	5,900
I	1,700	1.8	960
J	8,100	2.4	3,400
K	6,600	1.4	4,700
R	15,200	3.0	5,100
U	900	0.37	2,500
Vb	1,000	0.15	6,900
Y	18,000	2.4	7,500
Z+CC	4,900(d)	1.6	3,100

(a) Radon-222 in ventilation air, from mine waste piles, ore pile, and mine water discharged at surface. Basis: 1.025 x radon-222 in vent.

(b) Data furnished by mine operator.

(c) For these mines, the contribution of radon-222 from mine waste and ore piles was that estimated from pile dimensions and U_3O_8 content.

(d) Production from mines Z and CC were composited by the mine operator. Thus, we have composited their radon-222 output for comparison.

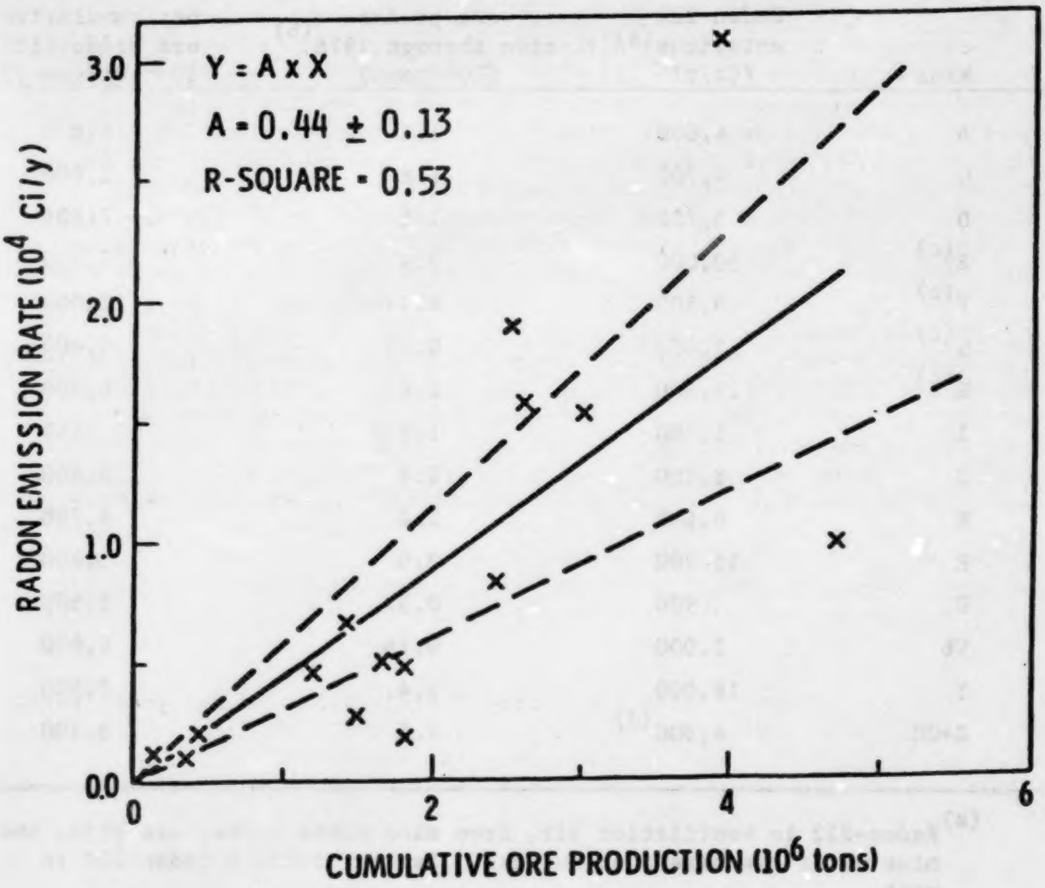

Figure 3-2. Relationship of annual radon-222 emission rate to cumulative ore production (Ja80).

annual radon-222 emissions can be predicted for each individual mine. Of course, the total annual radon-222 emissions from underground uranium mines for any particular year would be the sum of the emissions from all individual mines plus the relatively small contributions of radon-222 from aboveground sources.

The extensive amounts of data necessary to estimate future emissions on a mine-by-mine basis are currently unavailable. Therefore, EPA made two assumptions to develop an alternative forecasting procedure: 1) that the 27 mines included in the Battelle/PNL study (Ja80) comprised a representative sample of all underground uranium mines with respect to emissions, and 2) that the distribution of the number of active mines relative to cumulative ore production remains constant during the forecast period. In other words, any incremental increase in radon-222 emissions associated with increased cumulative ore production is offset by 1) closure and sealing of older mines, and 2) lower emission rates from new mines with relatively small cumulative production. Using the first assumption, EPA calculated total annual emissions of 240,000 Ci/y for all underground uranium mines in 1978; i.e., radon-222 emissions of 150,000 Ci/y were determined for those mines that accounted for 63 percent of the total U_3O_8 production. Therefore, total emissions from underground uranium mines can be estimated by scaling the measured emissions by the percentage of total production represented by the measured emissions. On an annual U_3O_8 production basis, 240,000 Ci/y is equivalent to 26 Ci/ton U_3O_8. With the second assumption, EPA used 26 Ci/ton U_3O_8 as a factor relating annual short tons of U_3O_8 to annual radon-222 emissions. Provided the average mine's cumulative ore production remains constant, future radon-222 emissions can be estimated by multiplying 26 Ci/ton U_3O_8 times the predicted annual production of U_3O_8 (in tons) for the year desired.

Table 3-4 presents estimated radon-222 emissions for the years 1978, 1982, 1983, 1985, and 1990. The U_3O_8 produced by underground uranium mines in 1978 and 1982 was obtained from the Department of Energy (DOE83). The U_3O_8 production estimates for 1985 and 1990 were taken from projections presented in Section 2.3.

Table 3-4. Predicted radon-222 emissions from underground uranium mine vents

Year	Estimated U_3O_8 production (short tons)	Predicted emissions (Ci/y)
1978	9,200	240,000
1982	6,200	160,000
1983	5,200	140,000
1985	3,100	80,000
1990	2,300	60,000

The estimated future emissions of radon-222 from underground uranium mines (Table 3-4) indicate a decreasing trend in annual radon-222 emissions through 1990; however, EPA's forecasting approach does not account for nonproduction-related factors that may influence radon-222 emissions. Therefore, the predicted radon-222 emissions should be used primarily to illustrate general trends.

3.3 Ambient Air Concentrations

3.3.1 New Mexico Study

In 1977, the New Mexico Environmental Improvement Division (NMEID) carried out a two-year study to determine 1) the soufces of high concentrations of airborne radioactivity in uranium-producing areas; 2) background radioactivity levels, as well as levels associated with uranium mines and milling facilities; and 3) the possibility that New Mexico standards were being exceeded (Bu83). In the Grants Mineral Belt, more than 1700 individual outdoor radon-222 air samples were collected and measured from 33 sites, and radon-222 decay product concentrations inside buildings and homes at 18 locations were documented. Radon-222 and radon-222 decay product data were analyzed statistically and compared with both background and current state and Federal standards. External radiation exposure rates were also measured at all radon-222 and radon-222 decay product sampling sites.

The NMEID study revealed that measured radon-222 concentrations in and near uranium mines exceeded New Mexico Radiation Protection Regulations (NMRPR) for an individual member of the public (3 pCi/liter in excess of background) at three of nine locations in the Ambrosia Lake region of the Grants Mineral Belt. These regulations, however, apply only to licensees (holders of radioactive material licenses) and registrants (individuals registered to use radiation machines) of the State of New Mexico; they do not apply to uranium mines.

The average yearly radon-222 concentration over the 2-year period reported by the NMEID for the Ambrosia Lake region was 4.0 pCi/liter; the highest yearly average value, measured near a trailer court that was sited close to a mine vent, was 6.4 pCi/liter. This trailer court is now shut down. Measured background radon-222 concentrations averaged approximately 0.5 pCi/liter. The results of the NMEID study are summarized in Tables 3-5 and 3-6 and in Figures 3-3 and 3-4. Statistical analyses and conclusions are presented in Table 3-7. The NMEID data appear to indicate that radon-222 emissions from uranium mines have indeed influenced ambient radon-222 concentrations.

The NMEID concluded that it would be inadvisable to locate any future housing in areas determined to be near or in excess of their radiation protection limits. The NMEID scientists also suggested that every effort be made to avoid future siting of mine vents near populated areas. The NMEID also recognized a need for documentating radon-222 background levels for definition of "background" in its radiation protection regulations.

Table 3-5. First-year radon-222 averages by station (Bu83) (pCi/liter)

Station	Mean	Standard deviation	Standard error	Sample number	P(normal)[a]	P(log-normal)[a]
201	1.12	1.15	0.28	17	<0.01	0.268
202	1.32	0.99	0.22	20	0.164	0.783
203	1.92	1.26	0.28	20	<0.01	<0.01
204	2.01	1.35	0.34	16	<0.01	0.456
205	1.55	1.14	0.28	17	<0.01	0.154
206	1.18	1.05	0.24	19	<0.01	0.830
208	1.10	0.97	0.27	13	0.049	0.428
209	0.72	0.69	0.16	18	0.01	0.357
210	1.55	1.31	0.30	19	0.01	0.074
211	0.44	0.46	0.10	20	0.01	0.822
212	0.36	0.45	0.10	21	0.01	0.064
302	1.37	0.70	0.16	19	0.354	0.877
305	0.76	0.68	0.16	19	0.034	0.354
307	0.63	0.73	0.18	17	0.01	0.588
309	0.30	0.29	0.07	19	0.180	0.521
310	0.41	0.49	0.12	17	0.01	0.827
313	0.48	0.37	0.08	20	0.017	0.056
315	0.57	0.55	0.12	22	<0.01	0.837
401	1.02	0.25	0.06	20	0.764	0.108
402	3.15	1.66	0.35	22	0.548	0.168
403	3.47	1.87	0.42	20	<0.01	0.540
406	2.96	1.85	0.44	18	0.566	<0.01
407	2.01	1.11	0.26	18	0.043	0.520
408	4.12	3.03	0.66	21	0.188	<0.01
409	3.59	3.32	0.76	19	<0.01	0.388
411	0.91	0.55	0.13	19	0.477	0.081
412	4.23	4.56	1.27	13	<0.01	0.427
414	1.50	1.17	0.27	19	0.037	0.469
500	0.13	0.08	0.05	3	0.640	0.975
501	0.10	0.03	0.02	3	0.154	0.122
502	0.10	0.05	0.03	3	0.05	0.069
Background[b]	0.57	0.69	0.06	122	<0.01	>0.15
Selected background[c]	0.42	0.34	0.07	25	<0.01	0.764
Ambrosia Lake[d]	3.20	2.53	0.24	110	<0.01	0.023
Anaconda[e]	1.06	0.75	0.12	38	<0.07	<0.01
UN-HP[f]	1.83	1.24	0.17	53	<0.01	<0.01

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[a] Probability that a normal/log-normal distribution would have a test statistic larger than that calculated for the data at each station. If values are less than 0.05, the distribution is not normal/log-normal using the 95% level of significance.

[b] Composed of all samples taken at stations 201, 209, 211, 212, 307, 313, 415, 500, 501, 502.

[c] Twenty-five samples chosen at random from all individual background samples.

[d] Pooled samples taken at stations 402, 403, 406, 407, 409, 412.

[e] Pooled samples taken at stations 302, 305.

[f] Pooled samples taken at stations 203, 204, 205.

Table 3-6. Second-year radon-222 averages by station (Bu83) (pCi/liter)

Station	Mean	Standard deviation	Standard error	Sample number	P(normal)[a]	P(Log-normal)[a]
201	0.81	0.75	0.17	20	0.011	0.544
203	1.51	1.11	0.24	22	<0.01	0.409
204	1.89	1.00	0.21	23	0.357	0.826
205	1.12	0.83	0.18	22	<0.01	0.631
206	0.93	0.83	0.19	20	0.015	0.210
208	0.84	0.64	0.14	20	0.016	0.917
209	0.79	0.57	0.12	23	0.072	0.167
210	1.41	1.35	0.31	19	0.015	<0.01
211	0.71	0.81	0.17	23	<0.01	0.249
212	0.61	0.59	0.14	18	0.042	0.266
302	0.78	0.50	0.11	21	0.404	0.097
305	0.95	0.76	0.17	21	<0.01	0.976
307	0.55	0.53	0.12	21	<0.01	0.024
309	0.21	0.13	0.03	21	0.386	<0.01
310	0.36	0.28	0.06	20	0.156	0.061
313	0.47	0.51	0.11	23	<0.01	0.536
315	0.49	0.37	0.08	24	0.030	0.048
401	1.18	0.43	0.10	19	0.303	0.12
402	6.40	3.28	0.66	25	<0.01	0.914
403	5.70	2.23	0.50	20	0.213	0.096
406	3.40	2.00	0.44	21	0.096	<0.01
407	3.23	1.55	0.32	23	0.773	0.035
408	5.77	3.59	0.77	22	0.470	0.246
409	5.43	3.58	0.75	23	0.360	<0.01
411	1.10	0.78	0.16	24	0.193	0.051
412	3.74	2.53	0.52	24	0.330	<0.01
414	1.69	1.23	0.26	22	0.050	0.436
415	0.14	0.22	0.05	19	<0.01	0.482
500	0.15	0.12	0.03	16	0.806	0.675
501	0.17	0.13	0.03	15	0.087	0.681
502	0.47	1.04	0.33	10	<0.01	0.456
Background[b]	0.51	0.62	0.05	188	<0.01	>0.15
Selected background[c]	0.53	0.73	0.15	25	<0.01	0.546
Ambrosia Lake[d]	4.66	2.89	0.25	136	0.091	<0.01
Anaconda[e]	0.87	0.64	0.10	42	<0.01	0.407
UN-HP[f]	1.51	1.02	0.12	67	<0.01	>0.15

---

[a] Probability that a normal/log-normal distribution would have a test statistic larger than that calculated for the data at each station. If values are less than 0.05, the distribution is not normal/log-normal using the 95% level of significance.

[b] Composed of all samples taken at stations 201, 209, 211, 212, 307, 313, 415, 500, 501, 502.

[c] Twenty-five samples chosen at random from all individual background samples.

[d] Pooled samples taken at stations 402, 403, 406, 407, 409, 412.

[e] Pooled samples taken at stations 302, 305.

[f] Pooled samples taken at stations 203, 204, 205.

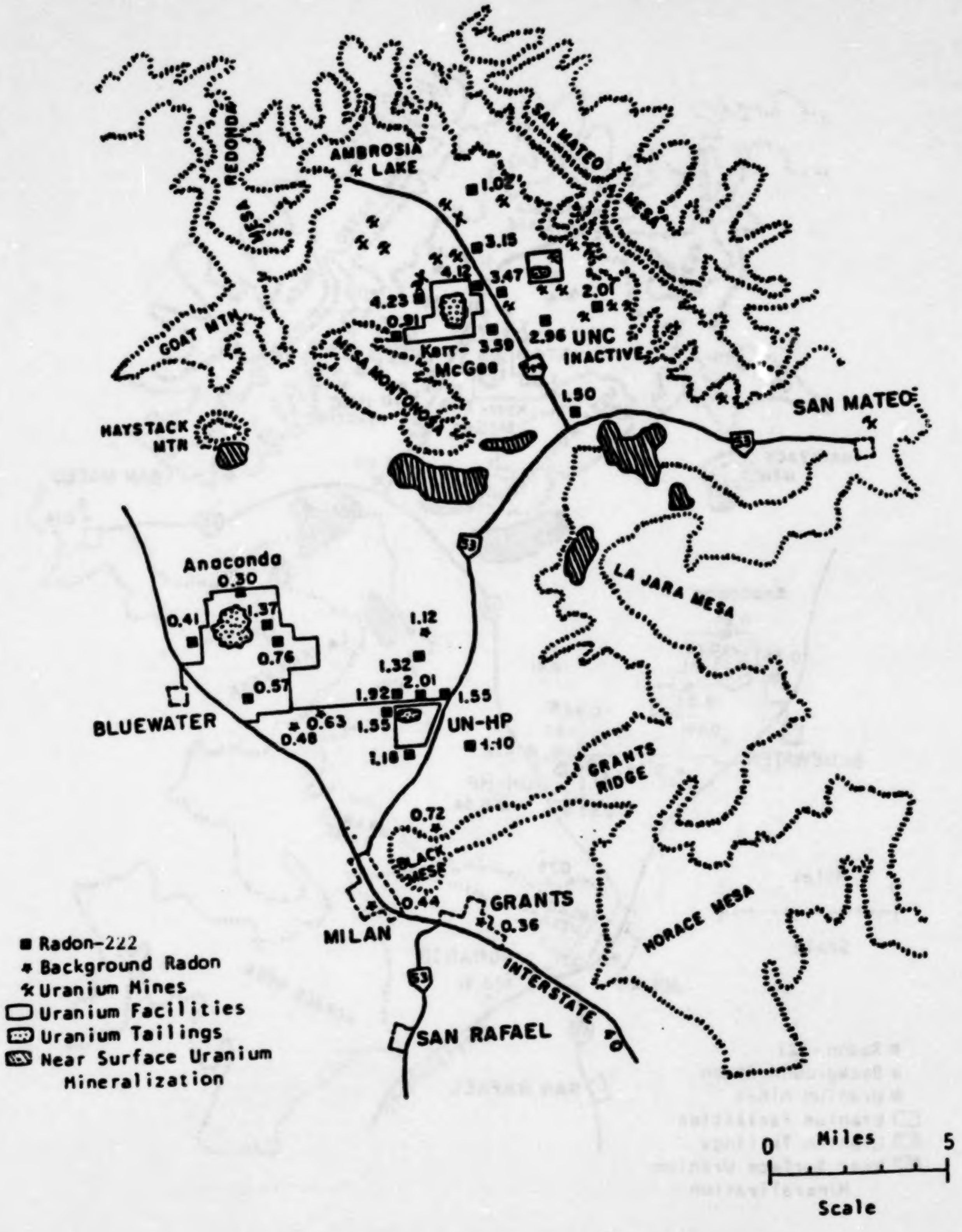
REDONDO MESA
AMBROSIA LAKE
SAN MATEO MESA
1.02
3.15
4.12
3.47
4.23
0.91
2.01
Kerr-McGee
3.59
2.96
UNC INACTIVE
GOAT MTN
MESA MONTONOSA
53
1.50
SAN MATEO
53
HAYSTACK MTN
53
LA JARA MESA
Anaconda
0.30
1.37
0.41
0.76
0.57
1.12
1.32
2.01
1.92
1.55
1.55
UN-HP
1.10
1.18
BLUEWATER
0.63
0.48
GRANTS RIDGE
0.72
BLACK MESA
0.44
GRANTS
0.36
MILAN
INTERSTATE 40
HORACE MESA
53
SAN RAFAEL
■ Radon-222
✱ Background Radon
⚒ Uranium Mines
☐ Uranium Facilities
▨ Uranium Tailings
▨ Near Surface Uranium Mineralization
Miles
0
5
Scale

Figure 3-3. First-year radon-222 averages by station (Bu83) (pCi/liter).

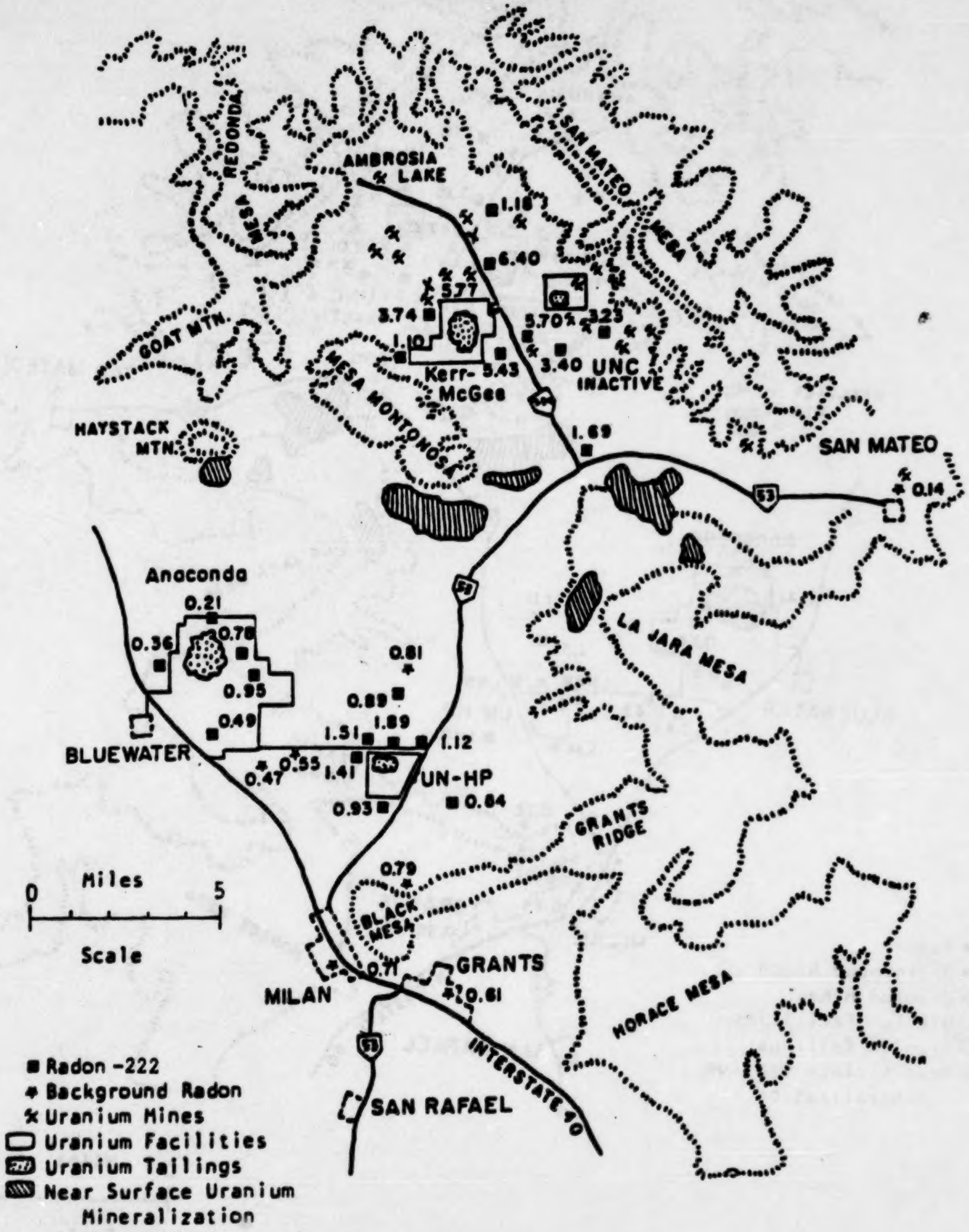
MESA REDONDA
AMBROSIA LAKE
SAN MATEO MESA
GOAT MTN.
HAYSTACK MTN.
MESA MONTONOSA
Kerr-McGee
1.18
6.40
5.77
3.74
1.10
5.43
5.70
3.23
3.40
UNC INACTIVE
1.69
SAN MATEO
0.14
53
Anaconda
0.21
0.78
0.36
0.95
0.49
BLUEWATER
0.81
0.89
1.89
1.51
1.12
0.55
0.47
1.41
UN-HP
0.93
0.84
LA JARA MESA
GRANTS RIDGE
0.79
BLACK MESA
0.71
GRANTS
0.61
MILAN
HORACE MESA
INTERSTATE 10
SAN RAFAEL
Miles
0
5
Scale
Radon -222
Background Radon
Uranium Mines
Uranium Facilities
Uranium Tailings
Near Surface Uranium Mineralization

Figure 3-4. Second-year radon-222 averages by station (Bu83) (pCi/liter).

Table 3-7. The t-test(a) probability values comparing radon-222 concentrations at mine mill stations with background(b) and regulatory limits (Bu83)

	Year One			Year Two		
Station	+3 pCi/ liter	+1 pCi/ liter	+0	+3 pCi/ liter	+1 pCi/ liter	+0
202	<0.01	0.337	<0.01	<0.01	<0.01	0.060
203	<0.01	0.047(c)	<0.01	<0.01	0.473	<0.01
204	<0.01	0.052	<0.01	<0.01	0.083	<0.01
205	<0.01	0.326	<0.01	<0.01	0.042	<0.01
206	<0.01	0.183	<0.01	<0.01	<0.01	0.051
208	<0.01	0.138	0.014	<0.01	<0.01	0.072
210	<0.01	0.337	<0.01	<0.01	0.363	<0.01
302	<0.01	0.396	<0.01	<0.01	<0.01	0.087
305	<0.01	<0.01	0.029	<0.01	<0.01	0.034
315	<0.01	<0.01	0.123	<0.01	<0.01	0.409
401	<0.01	<0.01	<0.01	<0.01	0.027	<0.01
402	0.236	<0.01(c)	<0.01	<0.01(d)	<0.01(c)	<0.01
403	0.445	<0.01(c)	<0.01	<0.01(d)	<0.01(c)	<0.01
406	0.158	<0.01(c)	<0.01	0.288	<0.01	<0.01
407	<0.01	<0.019(c)	<0.01	0.197	<0.01	<0.01
408	0.149	<0.01(c)	<0.01	<0.01(d)	<0.01(c)	<0.01
409	0.409	<0.01(c)	<0.01	0.010(d)	<0.01(c)	<0.01
411	<0.01	<0.01	<0.01	<0.01	0.26	<0.01
412	0.490	0.33(c)	<0.01	0.348	<0.01	<0.01
414	<0.01	0.381	<0.01	<0.01	0.298	<0.01

(a) One tailed t-test; it was assumed that the variances were unequal.

(b) The background data set consisted of 25 samples randomly selected from the 122 year-one samples (for year one) and the 188 year-two samples (for year two) collected at stations 201, 209, 211, 212, 307, 313, 415, 500, 501 and 502.

(c) These stations are significantly higher than background +1 pCi/liter. Unmarked significant stations are less than background +1 pCi/liter. Significant stations in the background (+0 column) are greater than background.

(d) These stations are significantly higher than background +3 pCi/liter. Unmarked significant stations are less than background +3 pCi/liter.

NMEID has conducted additional research pertaining to the impact of emissions from underground uranium mines on ambient radon-222 concentrations. However, a summary of the results, which will be published as Appendix C (Bu83), was not available to EPA.

3.3.2 Kerr-McGee Data

In 1983, Kerr-McGee Corporation compared monitored radon-222 and radon-222 decay product concentrations around uranium mines in the Ambrosia Lake area of New Mexico during periods of normal uranium mining operations and during partial shutdown periods (Sh83). During partial shutdown periods, either the Kerr-McGee mines or the Homestake mines were shut down; however, mines of both companies were not shut down simultaneously. The average radon-222 concentrations measured by Kerr-McGee near two underground uranium mines in the Ambrosia Lake area are shown in Tables 3-8 and 3-9. These data are presented as representative of the Kerr-McGee data. Other data are available in the Radian report (Sh83).

In a statistical analysis of the data, Radian Corporation (a consultant to Kerr-McGee) found no conclusive evidence that mining operations increased the radon-222 or radon-222 decay product levels in the area (Sh83). Radian concluded the following: "...the short-term variability in radon-222 and radon-222 decay product levels is probably greater than the contributions of the mines...at least for the study period. Given the large temporal variability, it is difficult to quantify the contribution of the mining operations accurately" (Sh83).

In a 1983 communication to EPA, Kerr-McGee states: "...radon released from mining and milling activities has no statistically discernible impact on natural environmental radon levels...radon concentrations during operations are not statistically different from radon concentrations during suspended operations, i.e., when only background sources of radon are present." Kerr-McGee concluded that local micrometeorology, rather than mining operations, is the dominant influence on ambient radon-222 and radon-222 progeny levels (Sh83).

3.3.3 Additional Study Needed

The NMEID data suggest that uranium mining operations have a substantial effect on nearby ambient radon-222 concentrations, while Kerr-McGee's data and statistical analysis argue against such a hypothesis. Additional study is needed regarding the relationship between emissions from underground uranium mines and ambient radon-222 concentrations near the mines.

Table 3-8. Radon-222 concentration (pCi/liter) for mine 1: days with at least 20 data points (Sh83)

	Before shutdown (May 15-June 13)	During Kerr-McGee shutdown (June 14-June 27)	During Homestake shutdown (June 28-July 11)	After shutdown (July 12-August 2)
Mean	4.07	2.95	3.73	6.60[a]
Median	4.55	2.75	3.57	4.98
Number of observations	9	9	10	18
Standard deviation	1.13	1.06	0.923	4.19
90% confidence interval for mean	(3.37, 4.77)	(2.29, 3.61)	(3.19, 4.27)	(4.88, 8.32)

(a) The six daily average values at the end of the after-period ranged from 8.07 to 17.2. The twelve values preceding these values ranged from 2.74 to 5.78. The six-day high period had a much larger effect on the mean than on the median.

Table 3-9. Radon-222 concentration (pCi/liter) for mine 2: days with at least 20 data points (Sh83)

	Before shutdown (May 15-June 13)	During Kerr-McGee shutdown (June 14-June 27)	During Homestake shutdown (June 28-July 11)	After shutdown (July 12-August 2)
Mean	5.15	4.39	4.68	6.63
Median	5.42	3.70	4.79	7.50
Number of observations	6	7	5	4
Standard deviation	0.585	1.71	1.19	1.82
90% confidence interval for mean	(4.67, 5.63)	(3.13, 5.65)	(3.55, 5.81)	(4.49, 8.77)

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Chapter 4: ESTIMATING THE RISK DUE TO EXPOSURE FROM RADON-222 DECAY PRODUCTS

4.1 Introduction

This chapter describes the methodology the EPA uses to estimate the exposure and the health detriment, i.e., lung cancer, due to radon-222 in the general environment. First, radon-222 exposure pathways are explained and the EPA risk model is described; then, estimates of risks due to radon-222 progeny (radon-222 decay products) made by various scientific groups are compared, and the risk coefficients to be used in this risk assessment are selected. Earlier studies have shown that all risk estimates have a degree of uncertainty (EPA84). Therefore, EPA uses more than a single coefficient to indicate the range of this uncertainty.

The occurrence of radiation-induced cancer is very infrequent when compared with the current incidence of all cancers. Even among heavily irradiated populations (e.g., some of the uranium mine workers in epidemiologic studies), the precision and accuracy of the number of lung cancers resulting from radiation is uncertain because of the small sampling segment and because of the large variability in the data. Also, the small sampling of exposed populations has not been followed for their full lifetime; therefore, information on the ultimate effects of their exposure is limited.

Although only human epidemiological data are used to derive risk estimates for effects of exposure to radon-222 progeny, animal studies support the risk estimates. In a series of studies with rats, French investigators have shown a dose-effect relationship similar to that obtained in surveys of uranium miners (Ch84, 85). In these studies, the risk per working level month at 20 cumulative working level months (CWLM) is about four times greater than at 3000 or more CWLM (Ch84, 85). The lowest exposure studied to date, 20 CWLM, is about 10 times the background exposure and has caused a doubling of lung cancer in the rats (Ch84, 85).

When considered in light of experiments with animals and various theories of carcinogenesis and mutagenesis, the observational data on cancers related to human exposure to radiation are subject to a number of interpretations. This, in turn, leads to differing estimates of radiation risks by both individual radiation scientists and expert advisory groups. Readers should bear in mind that estimating radiation risks is not a mature science and that the evaluation of the risk due to radon-222 decay products (progeny) will change as additional information becomes available. Nevertheless, a substantial data base is available for use in developing risk estimates, and the Agency believes these estimates can be used in the development of regulatory requirements.

4.2 Radon-222 Exposure Pathways

4.2.1 Physical Considerations

Radon-222 from underground mining operations enters the general environment from mine ventilation exhaust systems and through waste materials from mining operations. The half-life of radon-222 is 3.8 days; therefore, when it is released into the atmosphere, some atoms of gaseous radon-222 can travel thousands of miles through the atmosphere before they decay. As shown in Figure 4-1, the radon decay process involves seven principal decay products before the radon-222 becomes nonradioactive lead. The first four short half-life radioactive decay products of radon-222 are the most important sources of cancer risk. Members of the decay chain with relatively long half-lives (beginning with lead-210, which has a 22-year half-life) are more likely to be ingested than inhaled and, in general, present much smaller risks.

The principal short half-life products of radon-222 are polonium-218, lead-214, bismuth-214, and polonium-214. Polonium-218, the first decay product, has a half-life of just over 3 minutes. This is long enough for most of the electrically charged polonium atoms to attach themselves to microscopic airborne dust particles that are typically less than a millionth of a meter in diameter. When inhaled, these small particles have a good chance of sticking to the moist epithelial lining of the bronchi. Most inhaled particles are eventually cleared (removed) from the bronchi by mucus, but not quickly enough to keep the bronchial epithelium from being exposed to alpha particles from the decay of polonium-218 and polonium-214. This highly ionizing radiation passes through and delivers radiation doses to several types of lung cells.

Adequate characterization of the exact doses delivered to cells that eventually become cancerous cannot be made. Knowledge of the deposition pattern of the radioactive particles in the lung is based on theoretical models, and the distances from the radioactive particles to cells that are susceptible are assumed, not known. Further, there is some disagreement about the types of bronchial cells where cancer originates. Therefore, EPA estimates of lung cancer risk are based on the amount of inhaled radon-222 decay products to which people are exposed, rather than on the dose absorbed by the lung.

Ingrowth of Radon-222 Decay Products

At the point where radon-222 diffuses out of the interior mine surfaces, the concentration of associated radon-222 decay products is zero because those decay products generated prior to diffusion from the surface have been captured in earth. As soon as radon-222 is airborne, ingrowth of decay products commences and a secular equilibrium between the amount of radon-222 and the amount of each short half-life decay product is rapidly approached. At secular equilibrium, the activity of

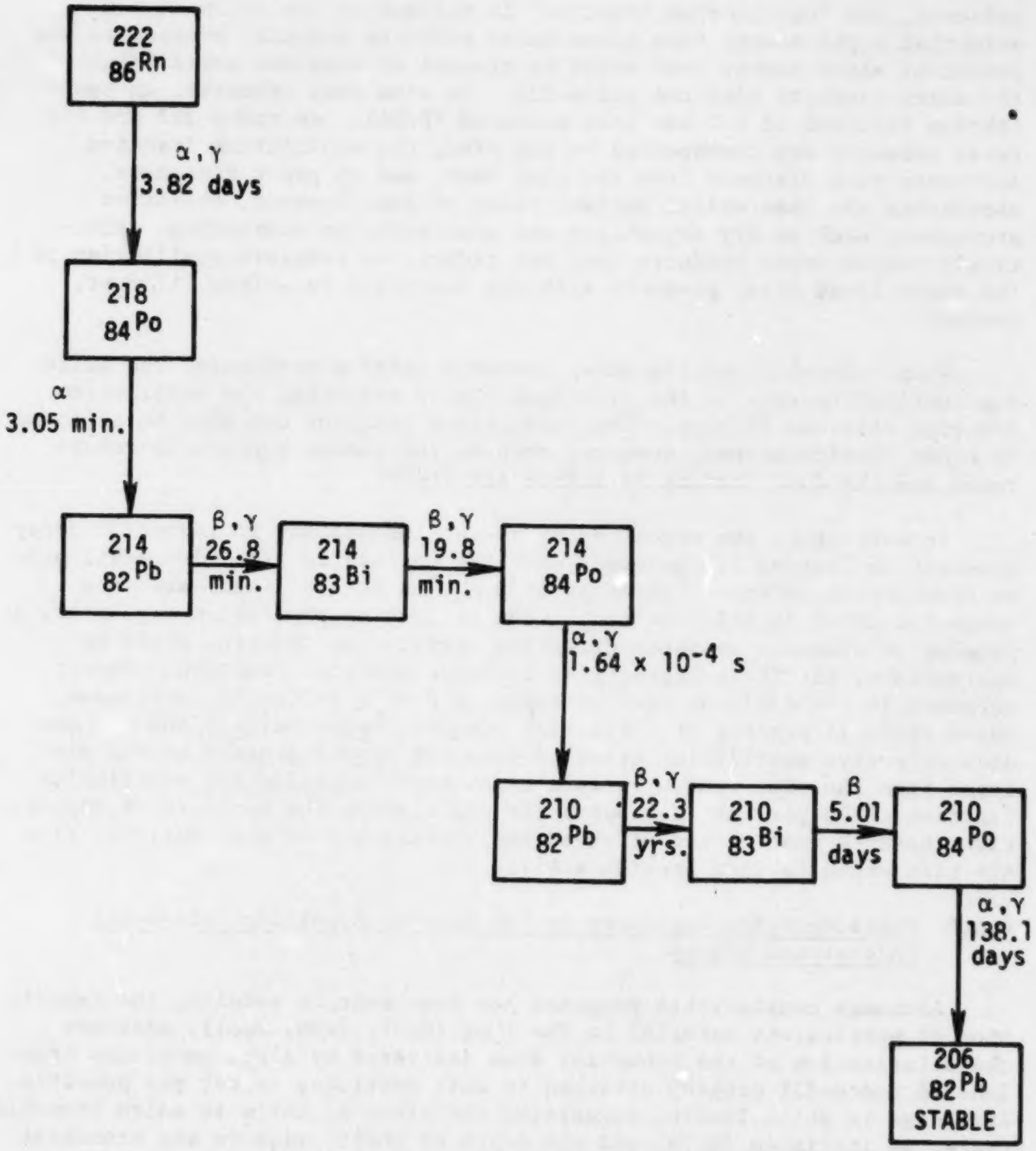
222 86 Rn
α, γ
3.82 days
218 84 Po
α
3.05 min.
214 82 Pb
β, γ
26.8 min.
214 83 Bi
β, γ
19.8 min.
214 84 Po
α, γ
1.64 x 10-4 s
210 82 Pb
β, γ
22.3 yrs.
210 83 Bi
β
5.01 days
210 84 Po
α, γ
138.1 days
206 82 Pb
STABLE

Figure 4-1. Radon-222 decay series.

radon-222 and all its short half-life decay products is equal and alpha activity per unit of radon-222 concentration is at its maximum value. As a means of accounting for incomplete equilibrium before this state is achieved, the "equilibrium fraction" is defined as the ratio of the potential alpha energy from those decay products actually present to the potential alpha energy that would be present at complete equilibrium of the decay products with the radon-222. In mine vent exhausts, an equilibrium fraction of 0.2 has been measured (Dr80). As radon-222 and its decay products are transported by the wind, the equilibrium fraction increases with distance from the mine vent, and at great distances, approaches the theoretical maximum value of one; however, depletion processes, such as dry deposition and precipitation scavenging, selectively remove decay products (but not radon), so complete equilibrium of the short-lived decay products with the radon-222 is seldom, if ever, reached.

When radon-222 and its decay products enter a structure, the building ventilation rate is the principal factor affecting the equilibrium fraction attained indoors. The equilibrium fraction can also be affected by other considerations, however, such as the indoor surface-to-volume ratio and the dust loading in indoor air (Po78).

In estimating the exposures of nearby individuals to radon-222 decay products in Chapter 5, the model uses the calculated effective equilibrium fraction at selected distances from a mine exhaust (see Table 4-4 presented later in this section). For estimating population exposures, a population-distance weighted effective equilibrium fraction would be appropriate, but it is impractical to calculate this fraction. Indoor exposure is the dominant form of exposure due to radon-222 [Americans spend about 75 percent of their time indoors (Mo76, Oa72)]; and the indoor effective equilibrium fraction does not depend greatly on the distance from the mine vent. In this assessment, an effective equilibrium fraction of 70 percent is assumed for calculating the exposure of populations because most of the affected individuals are at some distance from the mine exhausts (see Section 4.4.1).

4.2.2 Characterizing Exposures to the General Population vis-a-vis Underground Miners

Although considerable progress has been made in modeling the deposition of particulate material in the lung (Ha82, Ja80, Ja81), adequate characterization of the bronchial dose delivered by alpha particles from inhaled radon-222 progeny attached to dust particles is not yet possible. Knowledge is still lacking concerning the kinds of cells in which bronchial cancer is initiated (Mc78) and the depth of these cells in the bronchial epithelium. Current estimates of the exposure dose of inhaled radon-222 progeny actually causing radiogenic cancer are based on average doses, which may or may not be relevant (E185). Until more reliable estimates of the bronchial dose become available, following the precedents set in the 1972 and 1980 NAS reports appears to be a prudent approach (NAS72, NAS80). Therefore, the EPA estimates the risk due to radon-222 progeny on the basis of exposure rather than dose *per se*. This is called the epidemiological approach; i.e., risk is estimated on the basis of observed cancers following occupational exposure to radon-222 progeny.

Exposures to radon-222 decay products under working conditions are commonly reported in a special unit called the working level (WL). One working level is any concentration of short half-life radon-222 progeny having 1.3×10^5 MeV per liter of potential alpha energy (FRC67) [a WL is also equivalent to approximately 100 pCi/liter of radon-222 in secular equilibrium with its short-lived decay products]. This unit was developed because the concentration of specific radon-222 progeny depends on ventilation rates and other factors. A working level month (WLM) is the unit used to characterize a mine worker's exposure to one working level of radon-222 progeny for a working month of 170 hours. Inasmuch as the results of epidemiological studies are expressed in units of WL and WLM, comparable estimates of exposure were developed for members of the general population exposed to radon-222 progeny as explained below.

For a given concentration of radon-222 progeny, the amount of potential alpha energy a member of the general population inhales in a month is more than the amount a mine worker receives in a working month. Although members of the general population are exposed longer (up to 24 hours per day, 7 days a week), the average amount of air inhaled per minute (minute volume) is less in this group than that for a mine worker when periods of sleeping and resting are taken into account (EPA79). For comparison of the radon-222 progeny exposure of a mine worker with that of a member of the general population, one should compare the amount of potential alpha energy each inhales per year (Ev69).

The EPA assumes that a mine worker inhales 30 liters per minute (averaged over a work day). This average corresponds to about 4 hours of light activity and 4 hours of moderately heavy work per day (ICRP75). The new ICRP radon model, however, assumes an inhalation rate of 20 liters per minute for mine workers, which corresponds to 8 hours of light activity per day (ICRP81). Although this may be appropriate for nuclear workers, studies of the metabolic rate of mine workers clearly show that they are not engaged in light activity only (Sp56, ICRP75, NASA73). Therefore, 30 liters appears to be a more realistic estimate of the average minute volume for this group. Based on this minute volume, a mine worker inhales 3.6×10^3 cubic meters in a working year of 2000 hours (ICRP79). One working level of radon-222 progeny is 2.08×10^{-5} joules per cubic meter; therefore, in a working year, the potential alpha energy inhaled by a mine worker exposed to one working level is 7.5×10^{-2} joules.

According to the ICRP Task Group report on reference man (ICRP75), an inhaled air volume of 2.3×10^4 liters per day is assumed for adult males in the general population and 2.1×10^4 liters per day for adult females, or an average of 2.2×10^4 liters per day for members of the adult population. This average volume results in 1.67×10^{-1} joules per year of inhaled potential alpha energy from an exposure of an adult member of the population to one working level of radon-222 progeny for 365.25 days.

Although it may be technically inappropriate to quantify the amount of potential alpha particle energy inhaled by a member of the general population in working level months, this amounts to an annual exposure equivalent to 27 WLM (26.7) to an adult member of the general population exposed 24 hours a day. For indoor exposure, an occupancy factor of 0.75 (see above) is assumed; thus, an indoor exposure to one WL results in an annual exposure equivalent to 20 WLM (EPA79) in terms of the amount of potential alpha energy actually inhaled.

The smaller bronchial area of children as compared with adults more than offsets their lower per-minute volume; therefore, for a given concentration of radon-222 progeny, the dose to their bronchi, is greater. This problem has been addressed in a paper by Hofmann and Steinhausler (Ho77), in which they estimate that exposures received during childhood are about 50 percent greater than adult exposures. This information was used to prepare Table 4-1, which lists the age-dependent exposure used in the risk assessments described in the next subsection.* The larger exposure to children relative to that to adults increases the estimated mortality due to lifetime exposure from birth by about 20 percent.

Table 4-1. Potential alpha energy inhaled during one year of exposure to one working level (2.08×10^{-5} joules per cubic meter) as a function of age

Age of general population (years)	Potential alpha energy inhaled (joules)	WLM equivalence[(a)]
0-2	0.22	35
3-5	0.27	43
6-11	0.30	49
12-15	0.27	43
16-19	0.24	38
20-22	0.20	32
23 or more	0.17	27
Lifetime Average	0.195	31.4

(a) Assuming a WLM corresponds to about 6.2×10^{-3} joules of potential alpha particle energy inhaled (see text).

The exposure model just described has also been examined in terms of the average dose delivered to bronchial tissue using the most detailed dose model available--the five-lobe lung model developed by Harley and Pasternack (Ha82). For the breathing patterns assumed for each group, bronchial dose is 0.64 rad per WLM for mine workers and 0.51 rad for an adult member of the general population (Ha83). It appears that the factors not included in our simple model (e.g., the fraction of unattached radon-222 progeny) are not very important compared with other sources of uncertainty in the risk estimates.

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*The assumptions on minute volume, etc., for mine workers and the general population just described are the same as those used in the preparation of the EPA report entitled "Indoor Radiation Exposure Due to Radium-226 in Florida Phosphate Lands" (EPA79) and Final Environmental Impact Statements (EPA82, 83a).

4.3 Health Risk From Exposure to Radon-222 Decay Products

4.3.1 Risk Models

A wealth of data indicates that exposure to the bronchial epithelium of underground mine workers causes an increase in bronchial lung cancer, both among smokers and nonsmokers. Two recent reviews are of particular interest. The 1980 NAS BEIR-3 Report (NAS80) contains a review of epidemiological studies on mine workers. A lengthy report entitled "Risk Estimates for the Health Effects of Alpha Radiation," which was prepared by D. C. Thomas and K. C. McNeil for the Atomic Energy Control Board (AECB) of Canada, reanalyzes many of these epidemiological studies in a consistent fashion so that the modeling assumptions are the same for all of the data sets (Th82).

The manner in which radiogenic lung cancers are distributed in time, after a minimum induction period, is a crucial factor in numerical risk estimates. For radiation-induced leukemia and bone cancer, the period of risk expression is relatively brief; most occur within 25 years of exposure. For other radiation-induced cancers (including lung cancer), however, it appears that people are at risk for the remainder of their lives (NAS80). None of the epidemiological studies of underground mine workers provides information on lifetime expression; indeed, most of the study populations are still alive and still at risk. Lifetime risks cannot be estimated only on the basis of observations to date; therefore, a model is needed to project the risk beyond the period of direct observation. As discussed in the 1980 NAS BEIR report, there are two basic models of risk projection: (1) the absolute risk projection model, in which it is assumed that the observed annual numerical excess cancer per unit exposure (or dose) continues throughout life; and (2) the relative risk projection model, in which it is assumed that the observed percentage increase of the baseline cancer risk per unit exposure (or dose) is constant with time (NAS80).

In the case of lung cancer and most other solid cancers, a relative risk model leads to larger estimated risks than the absolute risk model because of the high prevalence of such cancers at old age. The number of lung cancer deaths that occurred in the U.S. population as a function of age in 1970 is shown in Figure 4-2. The decrease in the number of deaths for ages greater than 65 years is due to depletion of the population by competing risks, not a decrease in the age-specific incidence of lung cancer mortality, which is relatively constant until age 95 (NCHS73). The age-specific mortality of underground mine workers dying of radiogenic lung cancer shows the same pattern of death as a function of age as

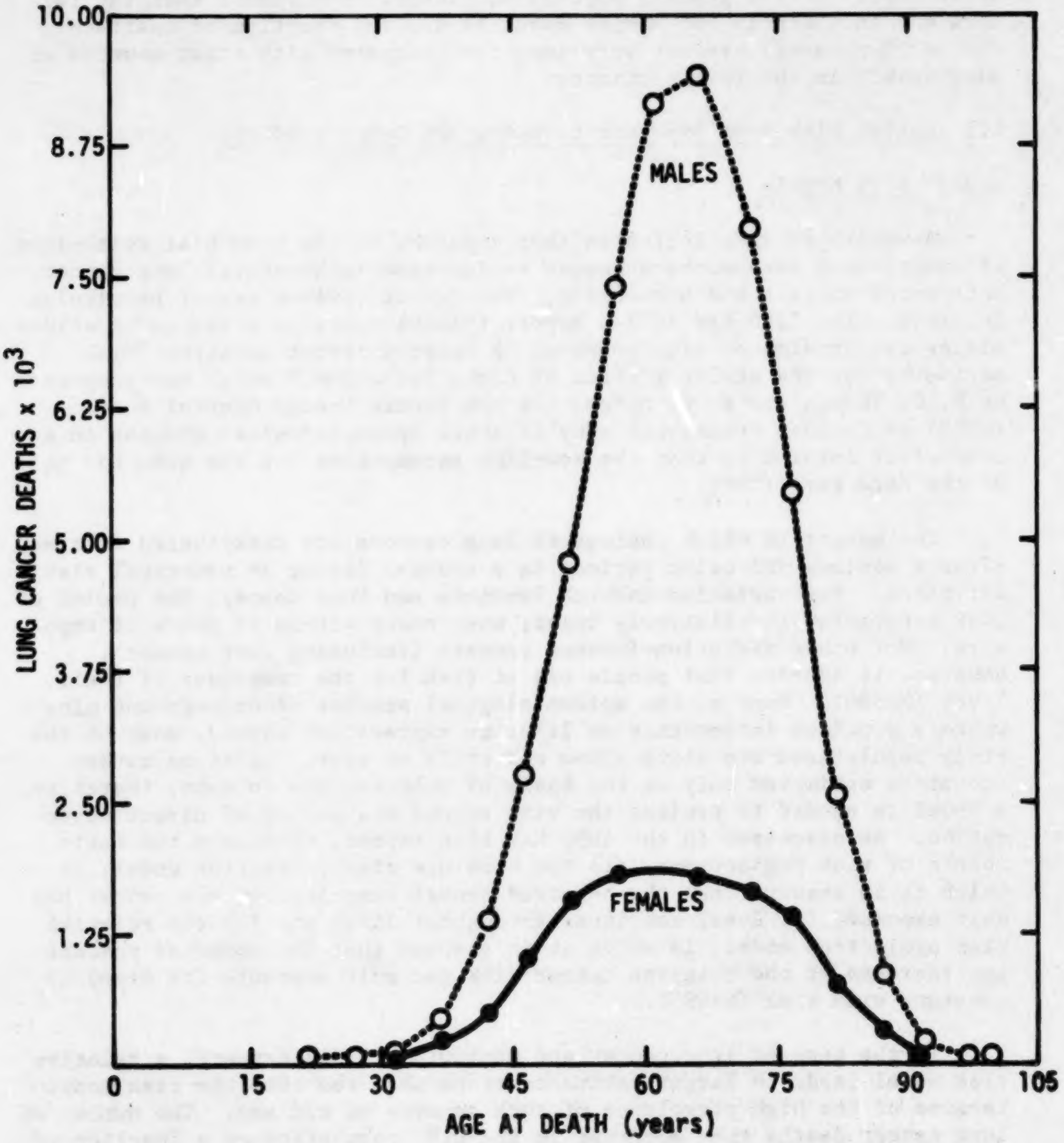

Figure 4-2. U.S. lung cancer mortality by age--1970.

the general male population (Ra84, E185). In a recent review (E185), it was shown that a relative risk model can adequately account for the temporal pattern of cancer deaths observed in underground mine workers, whereas absolute risk projection models fail to do so.

4.3.2 The EPA Relative Risk Model

Since 1978, the Agency has based risk estimates due to inhaled radon-222 progeny on a linear dose response function, a relative risk projection model, and a minimum induction period of 10 years. Lifetime risks are projected on the assumption that exposure to 1 WLM increases the age-specific risk of lung cancer by 3 percent over the age-specific rate in the U.S. population as a whole. The life table analysis described in Bu81 and EPA84 is used to project this risk over a full lifespan.

The EPA model has been described in detail (EPA79, E179). A review of this model in light of the more recent information described below revealed that the major assumptions, linear response, and relative risk projection have been affirmed. The A-bomb survivor data clearly indicate that the absolute risk of radiogenic lung cancer has continued to increase among these survivors, while their relative risk has remained reasonably constant (Ka82). The UNSCEAR, the ICRP, and the 1980 NAS Committee have continued to use a linear dose response to estimate the risk of lung cancer due to inhaled radon-222 progeny. Thomas and McNeill's analysis (Th82) indicates that the use of linearity is not unduly conservative and may, in fact, underestimate the risk at low doses. The 1980 NAS BEIR Committee reached a similar conclusion (NAS80).

A major limitation of earlier EPA risk estimates is the uncertainty in the relative risk coefficient used (3 percent increase in the age-specific lung cancer mortality rate per WLM). This value is based on the excess mortality caused by lung cancer among exposed mine workers of various ages, many of whom smoked. Therefore, it represents an average value for a mixed population of smokers, former smokers, and nonsmokers. This assumption may lead to an exaggerated risk estimate (as discussed below) because smoking was more prevalent among some groups of mine workers studied than it is among the U.S. general population today.

In a recent paper, Radford and Renard (Ra84) reported on the results of a long-term study of Swedish iron miners who were exposed to radon-222 progeny. This study is unique in that most of the miners were exposed to less than 100 WLM and the risks to smokers and nonsmokers were considered separately. The absolute risks of the two groups were similar, 20 fatalities per 10^6 person-year WLM for smokers compared with 16 fatalities for nonsmokers. The total number of lung cancer fatalities for nonsmokers is small; therefore, the estimate of 16 fatalities is not too reliable. Although absolute risks were comparable for the smoking and nonsmoking miners, relative risks were not because the baseline incidence of lung cancer mortality is much lower among nonsmokers than among smokers. This resulted in a relative risk for nonsmoking exposed miners relative to unexposed nonsmokers that was about four times larger than the relative risk for exposed smokers. This larger relative risk does not, however, fully compensate for the lower baseline incidence of nonsmokers. Therefore, this study indicates that a relative risk coefficient of 3 percent per WLM may be too high when applied to the population as a whole. Further followup of this and other groups of mine workers may provide more reliable data on the risk to nonsmokers, and EPA expects to incorporate separate consideration of smokers and nonsmokers into its analyses as more data become available.

Although occupational exposures to pollutants other than radon-222 progeny are probably not important factors in the observed lung cancer risk for underground mine workers (El79, Th82, Mu83, Ra84), the use of occupational risk data to estimate the risk of a general population is far from optimal, as it provides no information on the effect of radon-222 progeny exposures to children and women. Although the model continues to assume that the risk per unit exposure during childhood is no more effective than that occurring to adults, this assumption may not be correct. The A-bomb survivor data indicate that, in general, the risk from childhood exposure to low linear energy transfer (LET) radiation is greater and continues throughout life (Ka82). As yet, specific data for lung cancer have not been collected (Ka82). Another limitation of the data for underground mine workers is the absence of women in the studied populations. The A-bomb survivor data indicate that women are as sensitive as men to radiogenic lung cancer, even though they tend to smoke less as a group (Pr83). These data are not conclusive, however.

4.3.3 Other Risk Estimates

National Academy of Sciences BEIR-3

The National Academy of Sciences BEIR-3 Committee formulated an age-dependent absolute risk model with increasing risk for older age groups (NAS80). Estimates of the risk per WLM for various ages and the estimated minimum induction period for lung cancer following exposure (NAS80, pp. 325 and 327 respectively) are summarized in Table 4-2. These have been used to calculate the lifetime risk of lung cancer mortality from lifetime exposure to persons in the general population. This was done by means of the same life table analysis that was used to calculate other EPA risk estimates (Bu81).

Table 4-2. Age-dependent risk coefficients and minimum induction period for lung cancer due to inhaling radon-222 progeny (NAS80)

Age at diagnosis (years)	Excess lung cancers (cases per 10^6 person-year WLM)	Minimum induction period (years)
0-15	0	25
16-36	0	25-15
36-50	10	10
51-64	20	10
65 or more	50	10

The zero risk shown in Table 4-2 for those under 35 years of age at exposure does not mean that no harm occurs; rather, it means that the risk is not expressed until the person is more than 35 years old, i.e., only after the minimum induction period. The sequence of increasing risk with age shown in this table is not unlike the increase in lung cancer with age observed in unexposed populations; therefore, the pattern of excess risk over time is similar to that found by using a relative risk projection model.

Atomic Energy Control Board of Canada

Recently, Thomas and McNeil conducted a thorough analytical investigation of the incidence of lung cancer among uranium mine workers for the Atomic Energy Control Board (AECB) of Canada (Th82). These investigators tested a number of risk models on all of the epidemiological studies that contained enough data to define a dose-response function. They concluded that lung cancer per WLM among males increased 2.3 percent and that a relative risk projection model was more consistent with the incidence of excess lung cancer observed in groups of underground mine workers than any of the other models they tested. This is the only analysis that treated each data set in consistent fashion and used, to the extent possible, modern epidemiological techniques such as controlling for age at exposure and duration of followup.

The AECB estimate for lifetime exposure to Canadian males is 830 fatalities per million person WLM (Th82). For presentation in Table 4-3, this estimate has been adjusted to 600 fatalities per million person WLM (which would be the appropriate estimate for the U.S. 1970 general population) by determining the "best estimate" risk (see p. 114 in Th82). This estimate was then multiplied by the ratio of lung cancers caused by radon-222 in the U.S. 1970 general population to lung cancers in the U.S. 1970 male population as calculated in the EPA model. The 1978 reference life tables for Canadian males and U.S. males are quite similar; therefore, the simple proportional relationship of general population deaths to male deaths should give a reasonable estimate.

International Commission on Radiological Protection

The International Commission on Radiological Protection (ICRP) has made risk estimates for occupational exposure for working adults (ICRP81). The ICRP estimates (shown in Table 4-3) are based on an epidemiological approach; i.e., the exposure to mine workers in WLM and the risk per WLM observed in epidemiological studies of underground mine workers. The ICRP epidemiological approach assumes an average expression period of 30 years for lung cancer. Children, who have a much longer average expression period, are excluded from this estimate. The ICRP has not explicitly projected the risk to mine workers beyond the years of observation, even though most of the mine workers on whom these estimates are based are still alive and continuing to die of lung cancer.

Table 4-3. Estimated risk from exposures to radon-222 progeny[a]

Organization	Fatalities per 10^6 person WLM	Exposure period	Expression period	Reference
EPA[b]	760	Lifetime	Lifetime	EPA84
NAS BEIR-3[b]	730	Lifetime	Lifetime	NAS80
AECB[c]	600	Lifetime	Lifetime	Th82
ICRP	150-450	Working lifetime	30 years	ICRP81
UNSCEAR	200-450	Lifetime	40 years	UN77
NCRP[d]	130	Lifetime	Lifetime	NCRP84

[a] The number of fatalities per million-person WLM listed for EPA and NAS BEIR-3 differs from those previously published by EPA [860 fatalities per 10^6 PWLM and 850 fatalities per 10^6 PWLM, respectively (EPA83a)] because the increased potential alpha energy exposure during childhood is now included in the denominator (10^6 PWLM) of this ratio. The risk estimates for sources of radon-222 in the environment have not changed, because all were calculated in a life table analysis yielding deaths per 100,000 exposed rather than deaths per 10^6 PWLM.

[b] Assumes increased exposure during childhood, see Table 4-1.

[c] Adjusted for the 1970 U.S. general population, see text.

[d] Assumes risk diminishes exponentially with a 20-year halftime.

The ICRP has also made risk estimates based on a dosimetric approach. These estimates are in the lower part of the range shown for the ICRP estimate in Table 4-3. In their dosimetric approach, the ICRP assumes that the risk per rad for lung tissue is 0.12 of the risk of cancer and genetic damage following whole-body exposure (ICRP77). For exposure to radon-222 progeny, the ICRP divides this factor of 0.12 into two equal parts. A weighting factor of 0.06 is used to assess the risk from a high dose to bronchial tissue, where radiogenic lung cancer is observed in exposed underground mine workers. The other half of the lung cancer weighting factor, another 0.06 of the total body risk, is used to assess the risk to the pulmonary region, which receives a comparatively small dose from radon-222 progeny and where human lung cancer is seldom, if ever, found.

UNSCEAR

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimate shown in Table 4-3 is for a general population and assumes an expression time of 40 years (UNSCEAR77). Like the

ICRP, UNSCEAR did not make use of an explicit projection of risk of fatal lung cancer over a full lifetime.

National Council on Radiation Protection and Measurements

The National Council on Radiation Protection and Measurements (NCRP) risk estimate, the last entry in Table 4-3, is based on an analysis by Harley and Pasternack (Ha82). It is of particular interest because, like the EPA and AECB estimates, it is based on a life table analysis of the lifetime risk from lifetime exposure (NCRP84). This estimate uses an absolute risk projection model with a relatively low risk coefficient, 10 cases per 10^6 person WLM per year at risk, which is the smallest of those listed by the NAS BEIR-3 Committee (cf. Table 4-2). Moreover, they have assumed that the risk of lung cancer following irradiation decreases exponentially with a 20-year half-life and, therefore, exposures occurring early in life present very little risk.

The NCRP assumption of a 20-year half-life for radiation injury reduces the estimated lifetime risk by about a factor of 2.5. Without this assumption, the NCRP risk estimate would be the same as the midpoint of the UNSCEAR estimate (325 fatalities per million person WLM). The assumed decrease in risk as used by NCRP is questionable. If lung cancer risk decreased over time with a 20-year half-life, the excess lung cancer observed in Japanese A-bomb survivors would have decreased during the period this group has been followed (1950-1982); but to the contrary, their absolute lung cancer risk has increased markedly (Ka82).

4.3.4 Comparison of Risk Estimates

The EPA, NAS BEIR-3, AECB, UNSCEAR, ICRP, and NCRP estimates of the risk of lung cancer from inhaled radon-222 progeny are listed in Table 4-3. That the EPA, NAS (BEIR-3), and the AECB estimates are in agreement is expected as each of these estimates is based on lifetime exposure and lifetime expression of the incurred risk. Conversely, the three lower risk estimates shown in Table 4-3, either do not explicitly include these conditions or they include other modifying factors. Nevertheless, Table 4-3 indicates a divergence, by a factor of about 6, in risk estimates for exposure to radon-222 progeny. Thus, the use of a single risk coefficient may not be appropriate because it could give the impression that the risk is well known when obviously it is not. The EPA, BEIR-3, and AECB estimates may be slightly high because they represent relative risks based on adult males, many of whom smoked. The actual risk may be smaller for a population that includes adult females, children, and nonsmokers. The UNSCEAR and ICRP estimates are probably low because they represent absolute risk estimates that do not completely take into account the duration of the exposure and/or the duration of the risk during a lifetime. The NCRP estimate is likely to be very low, as a low risk coefficient was used in an absolute risk model and it was assumed that the risk decreases exponentially after the exposure.

To estimate the range of reasonable risks from exposure to radon-222 progeny for use in this document, EPA has averaged the estimates of

BEIR-3, the EPA model, and the AECB to establish an upper bound of the range. The lower bound of the range was established by averaging the UNSCEAR and ICRP estimates. The Agency chose not to include the NCRP estimate in its determination of the lower bound because this estimate is believed to be outside the lower bound. Therefore, the EPA has chosen risk coefficients of 300 to 700 fatalities per million person WLM as reasonable estimates for the possible range of effects from inhaling radon-222 progeny for a full lifetime. Although these two risk estimates do not encompass the full range of uncertainty, they seem to illustrate the breadth of much of current scientific opinion.

If a 1.2 percent relative risk coefficient were used instead of a 2.8 percent coefficient in the EPA relative risk model for calculating the lifetime risk of lifetime exposure, the estimated lung cancer mortality would be $300/10^6$ person WLM. If a 2.8 percent relative risk coefficient were used, estimated lung cancer mortality would be $700/10^6$ person WLM. In this document, risk estimates are presented for both these values (see Section 4.4.2).

4.4 Estimating the Risks

4.4.1 Exposure

The exposure to radon-222 progeny at a site of interest is based on the calculated radon-222 concentration and the calculated radon-222 progeny equilibrium fraction:

$$\underset{\text{(WL)}}{\text{Radon progeny concentration}} = \underset{\text{(pCi/liter)}}{\text{Radon concentration}} \times \underset{(f_e^{eff})}{\text{Radon progeny equilibrium fraction}} \times \underset{\text{(WL per pCi/liter)}}{9.84 \times 10^{-3}}$$

For individual risk estimation, emission data and meteorological data for the source and the EPA Industrial Source Complex Model (Bo79) are used to compute air concentrations of radon-222 at selected distances from a source or a group of such sources. For regional populations, emission data and meteorological data are used with the AIRDOS-EPA model (Mo79) to calculate air concentrations of radon-222; for national populations, emission data and meteorological data are used with the NOAA Trajectory Dispersion Model (NRC79). (Some examples of the calculations are presented in Chapter 5.)

Calculations of radon-222 progeny equilibrium fractions are based on distance from a source and the time required to reach the exposure site. By using the ingrowth model of Evans (Ev69) and the potential alpha energy data of UNSCEAR (UNSCEAR77), the outdoor equilibrium fraction can be calculated by the expression:

$$f_e^{out} = 1.0 - 0.0479e^{-t/4.39} - 2.1963e^{-t/38.6} + 1.2442e^{-t/28.4}$$

where t is the travel time in minutes.

Radon-222 and radon-222 progeny are in partial equilibrium at the mine exhaust vent (Dr80); therefore, an initial time correction must be made to ensure that correct equilibrium fractions are estimated outside of the mine.

An initial time (t_o) of 11.79 min, which is consistent with the observed equilibrium fraction of 0.2 in the mine vent (EPA80), is assumed. Then at a distance x (m), for a 3.5 m/s windspeed, the effective travel time t (min) is given by:

$$t = t_o + \frac{x}{3.5 \times 60}$$

where the factor of 60 converts the travel time from seconds to minutes.

The indoor equilibrium fraction presumes that those decay products associated with the radon-222 release also enter the building and that a ventilation rate of 1 h^{-1} (one air change per hour) in combination with indoor removal processes (e.g., deposition onto room surfaces) produces an indoor equilibrium fraction of 0.35 when there are no decay products in ventilation air and 0.70 when the decay products are in equilibrium with the radon-222 in the ventilating air (EPA83b). A simple linear interpolation is used:

$$f_e^{in} = 0.35\ (1 + f_e^{out}).$$

If one further assumes that a person spends 75 percent of his or her time indoors and the remaining 25 percent outdoors at the same location, the effective equilibrium fraction is given by:

$$f_e^{eff} = 0.75\ f_e^{in} + 0.25\ f_e^{out}$$

An example of the case for a 3.5 m/s windspeed and various distances from the source is given in Table 4-4.

Removal processes outdoors were assumed to limit the equilibrium fraction to 0.85, which corresponds to an indoor equilibrium fraction of 0.65 and an effective fraction of 0.70. Table 4-4 shows that this limit is reached at a distance of 17,000 meters.

4.4.2 Risk Estimation

After the exposure has been calculated, the risk can be estimated for an individual or a population.

Individual

Individual risks are calculated by using the life table methodology described by Bunger et al. (Bu81). Relative risk projections for lifetime exposure based on coefficients of 1.2 percent and 2.8 percent for the radiation-induced increase in lung cancer yield rounded-off estimates of

300 deaths/10^6 person WLM and 700 deaths/10^6 person WLM respectively. The risk coefficients of 1.2 percent and 2.8 percent were used in developing the risk assessments discussed in Section 4.3.4.

Table 4-4. Radon-222 decay product equilibrium fraction at selected distances from a mine vent[a]

Distance (m)	f_e^{out}	f_e^{in}	f_e^{eff}
0	0.200	0.420	0.365
100	0.207	0.422	0.369
150	0.210	0.424	0.370
200	0.213	0.425	0.372
250	0.216	0.426	0.373
300	0.219	0.427	0.375
400	0.226	0.429	0.378
500	0.232	0.431	0.381
600	0.238	0.433	0.384
800	0.251	0.438	0.391
1,000	0.263	0.444	0.397
1,500	0.293	0.453	0.413
2,000	0.323	0.463	0.428
2,500	0.351	0.473	0.442
3,000	0.379	0.483	0.457
4,000	0.432	0.501	0.484
5,000	0.482	0.519	0.510
6,000	0.528	0.535	0.533
8,000	0.612	0.564	0.576
10,000	0.682	0.589	0.612
15,000	0.812	0.634	0.679
>17,000	0.850	0.650	0.700

[a] Calculations presume an initial equilibrium fraction of 0.2 and a 3.5 m/s windspeed for the outdoor equilibrium fraction; an indoor equilibrium fraction of 0.35 for no radon-222 decay products in the ventilation air and 0.70 for ventilation air with 100 percent equilibrium between radon-222 and its decay products; and, for the effective equilibrium, 75 percent of time indoors and 25 percent of time outdoors.

Using these risk coefficients in the CAIRD Code (Co78), one can calculate the risk from any exposure to radon-222 progeny across any time period. Usually, the lifetime risk from lifetime exposure at a constant level is calculated. The age-specific differences in intake listed in

Table 4-1 are included in calculations of the lifetime risk. Results of representative calculations of lifetime risk are given in Table 4-5.

Table 4-5. Lifetime risk for lifetime exposure to a given level of radon-222 progeny

Radon-222 progeny concentration (WL)	Lifetime risk of lung cancer 700 deaths/ 10^6 person WLM	 300 deaths/ 10^6 person WLM
0.0001	1.58×10^{-4}	6.78×10^{-5}
0.001	1.58×10^{-3}	6.78×10^{-4}
0.01	1.56×10^{-2}	6.75×10^{-3}
0.1	1.42×10^{-1}	6.46×10^{-2}
0.2	2.55×10^{-1}	1.23×10^{-1}

The lifetime risk estimates shown in Table 4-5 are for lifetime exposure at a constant level of radon-222 progeny. These factors were used with WL exposures that were calculated by using radon-222 concentrations and an f_{e}^{eff} determined as detailed in Table 4-4 to estimate the risks listed in Table 5-5.

Regional

Collective (population) risks for the region are calculated from the annual collective exposure (person WLM) for the population in the assessment area by a computerized methodology known as AIRDOS-EPA (Mo79). An effective equilibrium fraction of 0.7 is presumed because little collective exposure takes place near the mine.

Formally, the annual collective exposure, S_E, can be defined as:

$$S_E = \int_0^\infty E n(E) dE$$

where S_E is the collective exposure (person WLM), E is the exposure level (WLM), and n(E) is the population density at exposure level E (person/WLM).

Practically, however, the collective exposure is calculated by dividing the assessment area into cells and then calculating the population, N_i (persons), and the annual exposure, E_i (WLM), for each one. The collective exposure is then calculated by the following expression:

$$S_E = \sum_i E_i N_i$$

where the summation is carried out over all the cells. Customarily, the regional population exposure is limited to persons within 80 km of the mine.

The population risk is calculated by using the same risk factors as for the individual risk calculations (700 deaths per 10^6 person WLM or 300 deaths per 10^6 person WLM).

National

Radon-222 released from mine vents can be transported beyond the 80-km regional cutoff. A trajectory dispersion model developed by NOAA (NRC79) has been used to estimate the national impact of radon-222 releases from mine vents. This model calculates the average radon-222 exposure to the U.S. population from unit releases at four typical uranium mining and milling sites. The model yields radon-222 concentrations (in picocuries per liter) in air, which are then converted to decay product exposures by assuming an effective equilibrium fraction of 0.7. National annual collective exposures (person WLM) are calculated for distances beyond the 80-km regional limit. The exposures and risks are calculated for a total population of 200 million persons.

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Chapter 5: RISK ASSESSMENT

5.1 Introduction

This chapter presents an assessment of the risks of fatal lung cancer caused by radon-222 emissions from underground uranium mines. Two measures of risk are presented: risks to nearby individuals and risks to the total population. The first measure refers to the estimated increased lifetime risk imposed upon individuals who spend their entire lifetime at a location near a mine where the predicted radon-222 concentrations are highest. Nearby individual risks are expressed as a probability, i.e., 0.001 (1/1000). This means that the increased chance of lung cancer in a person exposed for a lifetime is 1 in 1,000. Estimates of nearby individual risks must be interpreted cautiously, however, because few people generally reside at the location of highest risk or spend their whole lives at such locations. The second measure, total population risk, considers people exposed to all radon-222 concentrations, low as well as high. Expressed in terms of the number of fatal cancer cases caused by the amount of radon-222 emitted annually, it provides a measure of the overall public health impact. The risk estimates presented in this chapter were calculated by using the models and procedures described in Chapter 4.

The following approach was used in this chapter. First, an assessment was made of the risk to nearby individuals and the total population (both regional and national) from emissions from a reference (i.e., model) mine on a reference (i.e., model) site. Second, the total population risk from emissions from all underground uranium mines at selected time intervals was then assessed by using the emission rate estimates from Chapter 3. Finally, the risks to nearby individuals for specific "case study" mines were estimated for comparison of risks posed by actual mines with the reference mine risks.

5.2 Reference Underground Uranium Mine

5.2.1 Description

Radon-222 emissions from underground uranium mines (according to the age of these mines) are presented in Table 5-1. Estimated 1982 ore production rates from large uranium mines are presented in Table 5-2.

The parameters of the reference mine used in assessing the risks from radon-222 emissions are presented in Table 5-3. The reference mine

Table 5-1. Summary of radon-222 emissions from underground uranium mines according to age (Ja80)(a)

	New mines		Old mines	
Mine	Age (years)	Radon-222 emissions (Ci/y)	Age (years)	Radon-222 emissions (Ci/y)
A	3	7,400	-	-
B	9	4,500	-	-
C	9	4,600	-	-
D	7	3,600	-	-
E	-	-	21	29,800
F	-	-	20	9,400
G	4	1,800	-	-
H	-	-	21	15,200
J	-	-	20	7,900
K	-	-	19	6,400
L	-	-	29	1,400
R	-	-	20	14,800
U	4	900	-	-
V	2	1,000	-	-
Y	6	17,500	-	-
Z	-	-	17	2,600
Average	6	5,200	21	10,900

(a) Data from measurements made in 1978 and 1979.

Table 5-2. Estimated 1982 ore production of large underground uranium mines (Br84)

Mine	Estimated 1982 production (10^3 tons/y)
New mines (<10 years)	
King Solomon	38.0
Velvet	51.6
Tony M	137.6
Hack Canyon	63.1
Pidgeon	(a)
Kanab North	(a)
La Sal	81.7
Hecla	14.8
Big Eagle	16.6
Golden Eagle	(a)
Mt. Taylor	328.5
Old Church Rock	28.6
Church Rock-East	72.3
Kerr-McGee, Section 19	127.2
Nose Rock	(a)
Mariano Lake	36.8
Average	62
Old mines (≥10 years)	
Sunday	41.7
Dermo-Snyder	58.5
Wilson-Silverbell	16.5
Lisbon	73.3
Sheep Mountain	0
Church Rock-NE	171.9
Church Rock-1	176.8
Kerr-McGee	
Section 30-East	119.5
Section 30-West	132.4
Section 35	195.1
Section 36	111.2
Homestake	
Section 23	208.9
Section 25	67.9
Schwartzwalder	198.8
Average	112

(a) Not operational.

emissions and ore production rate in this table were developed from data in Tables 5-1 and 5-2. The reference mine is a large mine that has been in operation for about 20 years. The radon-222 emission rate from this reference mine is 11,000 Ci/y, the average value for older mines (in 1978-1979) as shown in Table 5-1. The mine has five vents arranged in the configuration shown in Figure 5-1.

Table 5-3. Reference underground uranium mine parameters

Parameter	Value
Ore grade	0.22 percent U_3O_8
Ore production	112,000 tons/y
Mine age	~20 years
Days of operation	250 days/y
Number of vents	5
Vent height	3 meters
Radon-222 emissions	11,000 Ci/y(a)

(a) 2,200 Ci/y from each vent.

Both horizontal and vertical vent configurations were used in assessing the radon-222 emissions from the reference mine. Horizontal vents were treated as ground-level releases (i.e., no plume rise). Vertical vents were modeled for plume rise by using the following parameters: exit velocity = 16.2 meters/sec, vent diameter = 1.5 meters, and exit temperature = 287°K. These represent average values from six mines for which actual vent data were available (Dr85).

5.2.2 Health Risk Assessment of the Reference Underground Uranium Mine

The lifetime risk to nearby individuals and the number of fatal cancers per year of operation due to radon-222 emissions from the reference underground uranium mine are presented in this section.

Risks to Nearby Individuals

The radon-222 concentrations in air near an underground mine are highly dependent upon a number of factors. The primary factors are emission rates and dispersion characteristics of the atmosphere, i.e., meteorological parameters. Other factors include the spatial distribution and orientation of the exhaust vents (vertical or horizontal) and the momentum flux of the exhaust air (velocity times flow rate). Plume rise due to the momentum flux can significantly affect the ground-level

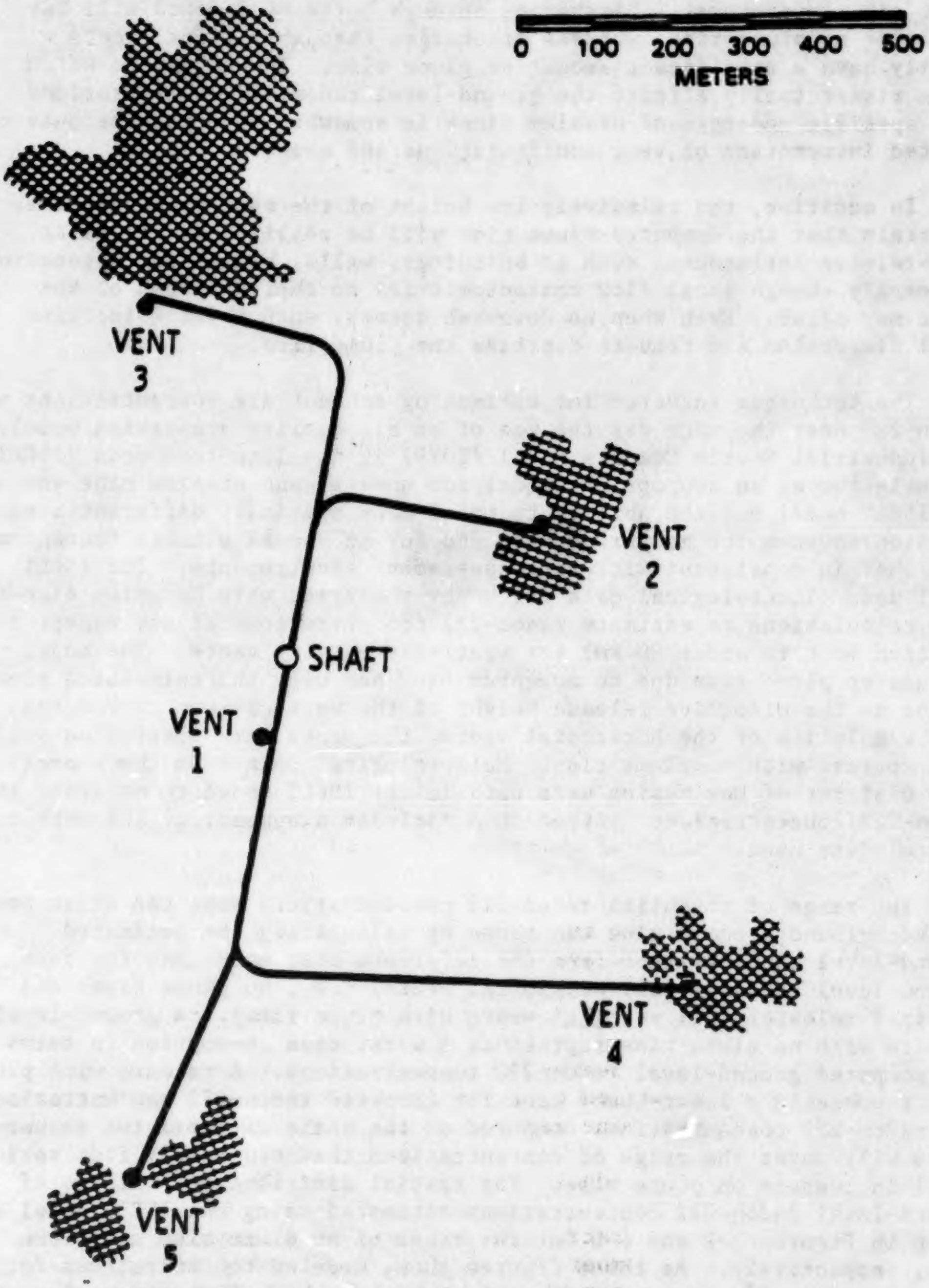
0
100
200
300
400
500
METERS
VENT 3
VENT 2
SHAFT
VENT 1
VENT 4
VENT 5

Figure 5-1. Reference underground mine.

radon-222 concentrations near the mine vents. Little buoyancy-induced plume rise is expected because the vent air streams are at or near ambient air temperatures. Discharges through horizontal vents will have little or no plume rise, whereas discharges through vertical vents will usually have a significant amount of plume rise. The extent to which plume rise actually affects the ground-level radon-222 concentrations near specific underground uranium mines is somewhat uncertain because of limited information on vent configurations and momentum fluxes.

In addition, the relatively low height of the vent releases makes it uncertain that the computed plume rise will be realized in all cases. Near-release influences, such as buildings, walls, hills, and vegetation, can easily change local flow characteristics so that downwash of the plume may occur. Even when no downwash occurs, such objects increase local dispersion and tend to decrease the plume rise.

The technique selected for estimating ambient air concentrations of radon-222 near the mine was the use of an air quality dispersion model. The Industrial Source Complex Model (Bo79) in its long-term mode (ISCLT) was selected as an appropriate model for underground uranium mine vents. The ISCLT model has the ability to model many spatially differentiated emission sources for many receptors and for an annual average concentration that is consistent with risk assessment requirements. The ISCLT model uses climatological data frequency summaries with Gaussian dispersion calculations to estimate radon-222 concentrations at any receptor location (out to about 80 km) for spatially varying vents. The model calculates plume rise due to momentum flux and uses the calculated plume height as the effective release height of the vertical vent. For the best simulation of the horizontal vents, the vents were treated as small area sources with no plume rise. Meteorological data from the Ambrosia Lake District of New Mexico were used in the ISCLT model to estimate the radon-222 concentrations. Appendix B includes a summary of the meteorological data used.

The range of potential radon-222 concentrations that can exist near an underground uranium mine was shown by calculating the estimated ground-level concentration from the reference mine emissions for both ground-level releases (all horizontal vents, i.e., no plume rise) and elevated releases (all vertical vents with plume rise). A ground-level release with no plume rise represents a worst-case assumption in terms of the computed ground-level radon-222 concentrations. A release with plume rise represents a lower-bound case for computed radon-222 concentrations. The radon-222 concentrations computed on the basis of these two assumptions will cover the range of concentrations that can result from various local influences on plume rise. The spatial distribution patterns of ground-level radon-222 concentrations estimated using the ISCLT model are shown in Figures 5-2 and 5-3 for the cases of no plume rise and plume rise, respectively. As these figures show, modeled concentrations for the reference mine are up to five times higher when all horizontal vents (no plume rise) are assumed compared with the case when all vents are

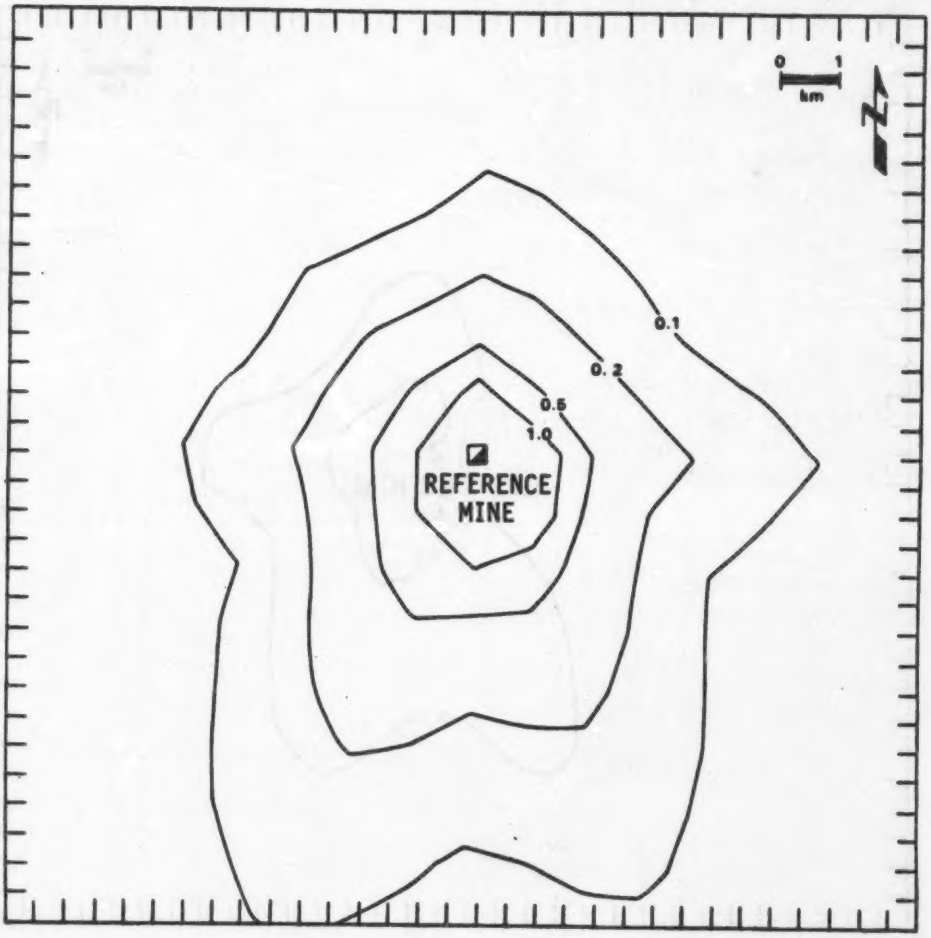
0
1
km
N
0.1
0.2
0.5
1.0
REFERENCE MINE

Figure 5-2. Modeled incremental radon-222 concentrations around the reference underground uranium mine, assuming no plume rise, pCi/liter (Dr85).

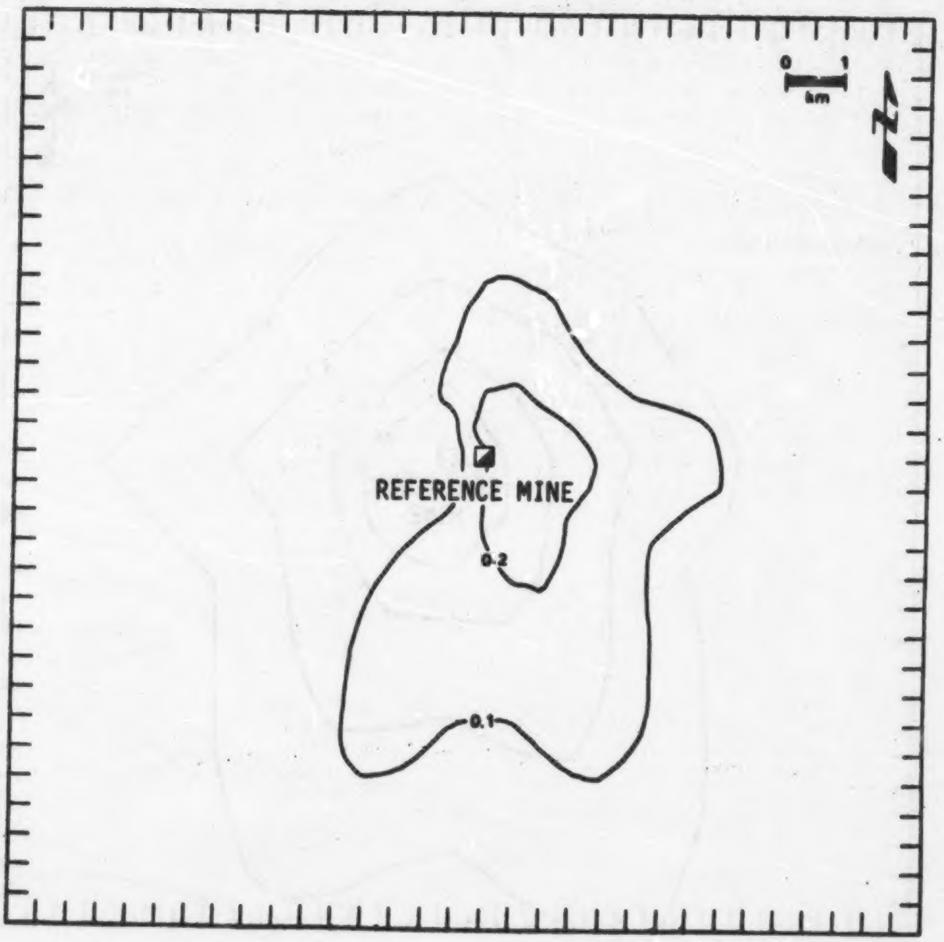
0
1
km
REFERENCE MINE
0.2
0.1

Figure 5-3. Modeled incremental radon-222 concentrations around the reference underground uranium mine, assuming a plume rise, pCi/liter (Dr85).

vertical (with plume rise). The shape of the isopleths of concentration is a function of the frequency distribution of meteorological parameters.

Table 5-4 shows the estimated radon-222 concentrations at various distances from the main shaft of the reference mine for releases with and without plume rise. The maximum concentration is the highest value that occurred at that distance at any of the 16 wind directions (i.e., sectors). Also shown is the average value of all sectors at each distance. In all cases, the maximum is about a factor of two higher than the average. The most likely radon-222 concentrations at these locations will fall somewhere within the range of values shown. Appendix B (Tables B-1 and B-2) includes a copy of the computer printout of these ISCLT model results.

Appendix E also shows the number and distribution of people living near large underground uranium mines in 1982. These data, obtained through a PNL field survey (Br84), showed that about 600 people lived within 2 kilometers of large underground mines in 1982. Many of the mines operating in 1982 have since been shut down; therefore, fewer people are now likely to be living in the areas surveyed in 1982.

Table 5-4. Estimates of radon-222 concentrations in air at selected distances from the reference underground uranium mine (Dr85) (pCi/liter)

Distance from mine shaft to receptor (m)	Computed with no plume rise (horizontal vents)		Computed with plume rise (vertical vents)	
	Maximum concentration in a sector	Average concentration for all sectors	Maximum concentration in a sector	Average concentration for all sectors
500	12	5.6	0.39	0.22
1,000	4.5	2.0	0.38	0.20
2,000	0.95	0.48	0.23	0.14
3,000	0.50	0.25	0.19	0.11
5,000	0.23	0.11	0.12	0.07
7,000	0.14	0.07	0.08	0.05
10,000	0.08	0.04	0.06	0.03

The estimated radon-222 concentrations from horizontal vent releases shown in Table 5-4 at 500 meters from the mine shaft is a worst-case situation, as the receptor is assumed to be located between a series of mine vents and relatively close (within a few hundred meters) to one of the vents. It is unlikely at the present time that such an extremely high concentration now actually exists near an underground uranium mine or that any persons are located at such a site.

Table 5-5 shows the estimated radon-222 decay product exposures and lifetime risks of fatal cancer to nearby individuals from radon-222 emissions from the reference mine. At a distance of 1000 meters from the

Table 5-5. Estimates of annual radon-222 decay product exposures and lifetime risks of fatal cancer at selected distances from the reference underground uranium mine

		Horizontal vents (no plume rise)			Vertical vents (with plume rise)		
Distance[(a)] (m)	f_e^{eff}[(b)]	Radon-222[(c)] (pCi/liter)	Annual exposure (WLM)	Lifetime risks to nearby individuals[(d)]	Radon-222[(c)] (pCi/liter)	Annual exposure (WLM)	Lifetime risks to nearby individuals[(d)]
500[(e)]	0.38	12.	1.4	7.0E-2 (3.0E-2)	0.39	4.6E-2	2.3E-3 (9.7E-4)
1,000	0.40	4.5	5.6E-1	2.8E-2 (1.2E-2)	0.38	4.7E-2	2.3E-3 (1.0E-3)
2,000	0.43	0.95	1.3E-1	6.3E-3 (2.7E-3)	0.23	3.1E-2	1.5E-3 (6.5E-4)
3,000	0.46	0.50	7.1E-2	3.5E-3 (1.5E-3)	0.19	2.7E-2	1.3E-3 (5.7E-4)
5,000	0.51	0.23	3.6E-2	1.8E-3 (7.7E-4)	0.12	1.9E-2	9.4E-4 (4.0E-4)
7,000	0.56	0.14	2.4E-2	1.2E-3 (5.1E-4)	0.08	1.4E-2	6.9E-4 (2.9E-4)
10,000	0.61	0.08	1.5E-2	7.5E-4 (3.2E-4)	0.06	1.1E-2	5.6E-4 (2.4E-4)

(a) Distance from mine shaft.

(b) Effective equilibrium fraction from Table 4-4.

(c) Radon-222 concentrations from Table 5-4.

(d) The values in the first column are based on a risk factor of 700 deaths/10^6 person WLM and the values in parentheses are based on a risk factor of 300 deaths/10^6 person WLM (see Chapter 4).

(e) This location is very close to one of the mine vents.

mine shaft, the estimated lieftime risk ranged from about 1 in 1000 to about 3 in 100.

Population Risks

The radon-222 decay product exposures and the number of fatal cancers per year of operation for the reference underground uranium mine are presented in Table 5-6. Estimates are presented for the regional population (i.e., population within 80 km of the mine) and the national population (i.e., population beyond 80 km). The number of fatal cancers per year of reference mine operation are estimated to vary from 0.02 to 0.05 in the regional population and 0.05 to 0.12 in the national population.

Table 5-6. Annual radon-222 decay product exposures and number of fatal cancers to the population due to radon-222 emissions from the reference underground uranium mine

	Regional population		National population	
Source	(Person-WLM/y)	(Fatal cancers/y of operation)[(a)]	(Person-WLM/y)	(Fatal cancers/y of operation)[(a)]
Underground uranium mine	68	4.8E-2 (2.0E-2)	170	1.2E-1 (5.1E-2)

[(a)] The values in the first column are based on a risk factor of 700 deaths/10^6 person WLM and the values in parentheses are based on a risk factor of 300 deaths/10^6 person WLM (see Chapter 4).

The regional population risks shown are for a reference site in the Ambrosia Lake District of New Mexico with a regional population of 36,000. Table 5-7 lists the characteristics of the reference site. The national population risks were estimated by using exposure data from a trajectory dispersion model developed by NOAA (Tr79). This model calculates a collective radon-222 exposure of 7 x 10^4 person-pCi/m^3 to the population of the United States from a 1 kCi radon-222 release from Grants, New Mexico; it does not include exposures to the regional population. Based on an equilibrium fraction of 0.7, the collective radon-222 decay product exposure to the U.S. population is estimated to be 15 person-WLM per kCi of radon-222 released from Grants, New Mexico.

Table 5-7. Characteristics of reference site

Characteristic	Value
Location	Latitude: 35°21'28" Longitude: 107°50'17"
Meteorological data	Grants/Gnt-Milan (WBAN=93057)
Stability categories	A-F
Period of record	54/01-54/12
Annual rainfall	20 cm
Average temperature	13.2°C
Average mixing height	800 m
Population	
0-8 km	0 persons
0-80 km	3.60E+4

5.3 Health Risk From Radon-222 Emissions From All Underground Uranium Mines

Estimates of the health risks from radon-222 emissions from all underground uranium mines for the years 1978, 1982, 1983, 1985, and 1990 are shown in Table 5-8. These estimates were based on emission estimates previously presented in Table 3-4 and used the following risk factors, which were developed from the reference mine data:

- Regional population risk/kCi of radon-222:
  0.0044 to 0.0018 fatal cancers/kCi
- National population risk/kCi of radon-222:
  0.011 to 0.0046 fatal cancers/kCi.

Table 5-8. Estimates of health risks from radon-222 emissions from all underground uranium mines for selected years

	Population segment (number of fatal cancers/y)[a]		
Year	Regional	National	Total
1978	1.1 (0.43)	2.6 (1.1)	3.7 (1.5)
1982	0.70 (0.29)	1.8 (0.74)	2.5 (1.0)
1983	0.62 (0.25)	1.5 (0.64)	2.1 (0.89)
1985	0.35 (0.14)	0.88 (0.37)	1.2 (0.51)
1990	0.26 (0.11)	0.66 (0.28)	0.92 (0.39)

[a] The values in the first column are based on a risk factor of 700 deaths/10^6 person-WLM and the values in parentheses are based on a risk factor of 300 deaths/10^6 person-WLM (see Chapter 4).

5.4 Case Study Mines

5.4.1 Description

As a part of an evaluation of radon-222 concentrations in air near underground uranium mines, Droppo (Dr85) estimated the radon-222 concentrations in air around 14 case study mines. The data for two of these case-study mines (11 and 12--large mines located in the Ambrosia Lake District of New Mexico) are presented in this section. These were the only mines in the study for which actual emission measurement data, vent release characteristics, vent configurations (horizontal or vertical), and meteorological data were available. The emission rate data and the vent release characteristics used were from the 1978-1979 PNL study (Ja80). The vent configuration information was supplied by the mining company in 1984. The meteorological data were from the Ambrosia Lake District of New Mexico.

5.4.2 Health Risk Assessment of Case Study Mines

The radon-222 concentrations in air near case study mines 11 and 12 were estimated with the ISCLT model (Bo79). The input data and the computed radon-222 concentrations are presented in Appendix B (Tables B-3 and B-4). The estimated annual average radon-222 concentrations in air at selected distances from case study mines 11 and 12 are presented in Table 5-9. The estimated radon-222 decay product exposures and individual lifetime risks to nearby individuals from the radon-222 emissions from case-study mines 11 and 12 are presented in Table 5-10. The estimated lifetime risk of fatal cancer to a nearby individual at 1000 meters from the mine shaft was 2 to 4 x 10^{-3} for mine 11 and 2 to 5 x 10^{-3} for mine 12. These values are similar to those estimated for radon-222 emissions from the reference mine. The values for the case-study mines fall within the range of values estimated for the reference mine.

Table 5-9. Estimates of radon-222 concentrations in air at selected distances from the case study mines 11 and 12 (pCi/liter)

Distance from mine shaft to receptor (m)	Case-study mine 11 Maximum concentration in a sector	Case-study mine 11 Average concentration for all sectors	Case-study mine 12 Maximum concentration in a sector	Case-study mine 12 Average concentration for all sectors
500[a]	7.2	1.4	5.0	1.6
1,000	0.65	0.36	0.79	0.40
2,000	0.30	0.14	0.24	0.12
3,000	0.12	0.078	0.13	0.065
5,000	0.073	0.043	0.062	0.035
7,000	0.053	0.029	0.039	0.019
10,000	0.037	0.019	0.024	0.011

[a] This location is very close to a mine vent for each of the two mines.

Table 5-10. Estimates of annual radon-222 decay product exposures and lifetime risks of fatal cancer at selected distances for case study mines 11 and 12

		Mine 11			Mine 12		
Distance[a] (m)	f_e^{eff}[b]	Radon-222[c] (pCi/liter)	Annual exposure (WLM)	Lifetime risks to nearby individuals[d]	Radon-222[c] (pCi/liter)	Annual exposure (WLM)	Lifetime risks to nearby individuals[d]
500[e]	0.38	7.2	8.5E-1	4.2E-2 (1.8E-2)	5.0	5.9E-1	2.9E-2 (1.2E-2)
1,000	0.40	0.65	8.0E-2	3.9E-3 (1.7E-3)	0.79	9.7E-2	4.8E-3 (2.1E-3)
2,000	0.43	0.30	4.0E-2	2.0E-3 (8.6E-4)	0.24	3.2E-2	1.6E-3 (6.7E-4)
3,000	0.46	0.12	1.7E-2	8.4E-4 (3.6E-4)	0.13	1.9E-2	9.4E-4 (4.0E-4)
5,000	0.51	0.073	1.2E-2	5.9E-4 (2.5E-4)	0.062	9.8E-3	4.9E-4 (2.1E-4)
7,000	0.56	0.053	9.1E-3	4.5E-4 (1.9E-4)	0.039	6.7E-3	3.3E-4 (1.4E-4)
10,000	0.61	0.037	7.0E-3	3.5E-4 (1.5E-4)	0.024	4.5E-3	2.2E-4 (9.6E-5)

[a] Distance from mine shaft.

[b] Effective equilibrium fraction from Table 4-4.

[c] Radon-222 concentrations from Table 5-9.

[d] The values in the first column are based on a risk factor of 700 deaths/10^6 person WLM, and the values in parentheses are based on a risk factor of 300 deaths/10^6 person WLM (see Chapter 4).

[e] This location is very close to one of the mine vents.

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Chapter 6: CONTROL TECHNIQUES

6.1 Introduction

Many factors affect the amount of radon-222* emitted to air from an underground uranium mine; however, a strong relationship exists between the amount of radon-222 exhausted and the total surface area of the underground mining activities being ventilated (Ja79 and Ja80), because the greatest source of radon-222 emanation is exposed ore and migration of the gas through surface fissures. The surface area within a mine is a function of the cumulative amount of ore extracted; therefore, the emission of radon-222 from underground mines tends to increase with increasing age of the mine.

Little is known about the actual control of atmospheric emissions of radon-222 because, to date, all control measures have emphasized limiting the in-mine exposure of mine workers to radon-222. Thus, the practice is to remove radon-222 from the mine, which ultimately means releasing it to the atmosphere. Knowing the source of radon-222 and the means by which it reaches the surface makes it possible to devise and evaluate conceptual control techniques.

In concept, radon-222 emissions from underground mines can be reduced by one of two basic approaches: 1) treat the mine ventilation air stream to remove radon-222, or 2) prevent the release of radon-222 into the mine air.

Available treatment methods of the mine ventilation air stream include various processes of adsorption, absorption, and separation. These treatment systems have the potential for high control efficiencies for radon-222, but they are largely unproven and tend to be costly because of the large volume of air that must be treated. Also, some of the techniques will produce a waste stream that must be disposed of, and therefore involve additional expenditures.

Available techniques to prevent the release of radon-222 into mine air include sealing exposed surfaces with impermeable coatings, backfilling worked-out areas, and bulkheading inactive areas. These techniques conform more readily to current mining practices and have the potential of reducing radon-222 emissions and ventilation air requirements in an operating mine. Although some mines practice some combination of these methods for employee protection, very little has been done to modify these practices to include the reduction of emissions to the atmosphere. Detailed discussions of the two approaches to radon-222 control are presented in the following subsections.

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* Radon in this text refers to radon-222 in all cases.

6.2 Controlling Radon-222 in Mine Ventilation (Exhaust) Air

The cost-effective removal of low levels of radon-222 from large volumes of air is extremely difficult. Numerous possible methods for reducing atmospheric emissions of radon-222 in mine ventilation (exhaust) air have been examined or suggested by various investigative studies. These approaches include adsorption on activated charcoal, surface adsorption on molecular sieves, cryogenic condensation, separation with semipermeable membranes, gas centrifuge separation, absorption, chemical reaction, and several hybrid or combination systems. None of these systems is currently in use in the industry; nor have any of them been tried out in a mine.

Each approach is discussed briefly, and pertinent results of prior studies (with respect to costs and practical application) are summarized. The cost figures presented herein are believed to be low for several reasons. Cost values were originally derived by Arthur D. Little in a 1975 study for the Bureau of Mines (Li75) and were based on small-capacity [2.36-m^3/s (5000-scfm)] systems intended for in-mine application and for operation about 50 percent of the time (2 shifts/day, 260 days/yr). Actually, radon-222 control of mine ventilation air would require systems capable of handling air streams of hundreds of thousands of cubic feet per minute and operating continuously. From an economic and/or technical standpoint, the methods do not offer promise as a practical means of controlling radon-222 emissions in the large-volume air streams encountered in mine ventilation exhausts.

6.2.1 Adsorption

Adsorption is a molecular surface phenomenon in which molecules of a fluid contact and adhere to the surface of a solid. By this process gases, liquids, or solids--even at very small concentrations--can be selectively captured and removed from air streams by use of adsorbent materials. Commonly used adsorbents are activated carbon (charcoal), silica gel, alumina, and bauxite. For practical reasons, activated carbon is the one exclusively used for waste gas cleanup; the others are used primarily for dehydration of air and gases.

Adsorption on Activated Carbon

The majority of radon-222 removal studies have centered on the use of activated carbon for radon-222 adsorption (Li75). Findings of these investigations can be summarized as follows:

- Radon-222 gas can be adsorbed from air by various activated carbons.

- The capacity of a given carbon to adsorb radon-222 depends on the volumetric flow rate of air rather than on the quantity of radon-222 (radon-222 concentration) adsorbed.
- For maximum carbon bed utilization, air velocities should be kept as low as possible. Air velocities between 0.5 and 2.5 liters/cm^2-minute have been suggested.
- The very small radon-222 concentrations in mine ventilation air require increased contact time between the radon-222 and carbon adsorbents, which, in turn, dictates relatively large carbon beds to accommodate the low flow rates through the beds.
- The capacity of a given carbon to adsorb radon-222 is reduced by moisture in the gas stream and such moisture must be considered in system sizing and design.
- The capacity of a given carbon to adsorb radon-222 is strongly influenced by temperature. The volume of air cleaned per unit of carbon mass decreases exponentially with temperature.

Applicability. The quantity of carbon materials (bed size) must be sufficient to accommodate the low-level radon-222 concentration, humidity, and temperature characteristics of the mine ventilation air. Thus, a major practical problem with activated carbon adsorption is the large carbon bed size (and attendant pressure drop) necessary to clean the ventilated air at the typical rates used in operating mines. Also, prevention of re-entrainment of the radon-222 requires that the carbon bed not only be of sufficient capacity, but that it be arranged in a manner that will permit the radon-222 to decay before regeneration of the carbon.

The A. D. Little study (Li75) suggests that there is sufficient adsorption capacity, even at 100 percent relative humidity and ambient temperatures, to permit development of a practical air cleaning system. Based on the given temperature dependency of activated carbon, this report considered several different inlet temperatures in the development of possible system designs. For inlet temperatures at ambient, 2°C, and -20°C, an alternating two-bed system with cyclical charcoal regeneration and a design effectiveness of 90 percent was used. For an air inlet temperature of -80°C, a single-bed system (90 percent effective) was proposed with a 12.7-day radon-222 retention time and needing no regeneration. Both systems were designed for an air flow of 2.36 m^3/s (5000 scfm) through 4660 pounds of charcoal for a 1-hour period. A pressure drop of 25 cm (10 inches) H_2O was required to clean 500 pCi/liter of radon-222 from a gas stream.

Costs. Estimated costs by Little (Li75) were based on the use of 72 of the 2.36-m^3/s (5000-cfm) units described above, an annual U_3O_8 production rate of 590,000 pounds, and a total mine ventilation rate of 170 m^3/s (360,000 cfm). Inflating the 1975 values to 1984 dollars gives costs of \$18/pound of U_3O_8 (for the dual-bed system) and \$46/pound of U_3O_8 (for the single-bed system). These values would equate to approximately \$71 and \$177 per ton of ore mined, respectively.

The radon-222 is retained on the carbon until decay takes place, and the carbon is then regenerated and reused; therefore, no byproducts or waste streams of environmental significance are generated by carbon adsorption systems. Activated carbon also could be applied within the mine for effective cleaning of smaller volumes of air.

Adsorption by Molecular Sieves

Molecular sieve is a term used to characterize solid hydrated metal crystalline materials, such as aluminosilicates. These aluminosilicates (zeolites), both natural and synthetic, have been used in a variety of processes for separating gases or liquids and as catalytic support materials. Molecular sieves have a high capability for surface adsorption, either chemical or physical, and tend to adsorb polar molecules and small-dimension atoms and molecules preferentially. For example, water vapor can be removed very effectively by molecular sieves.

In general, the zeolite's mode of action is the preferential adsorption of small molecules that fit into the pores. Thus, radon-222 with a relatively large atomic radius would be excluded from the normal zeolites rather than captured. If a molecular sieve with a pore size large enough to adsorb radon-222 were developed, all of the other atmospheric species (O_2, N_2, H_2O, etc.) would also be retained. Thus, a molecular sieve would have to have a greater preference for physically adsorbing radon-222 than any of the other major atmospheric species. The activated carbons are far superior to molecular sieves for adsorbing radon-222; therefore, no further consideration should be given to molecular sieves.

6.2.2 Cryogenic Condensation

Radon-222, which has a normal boiling point of 211°K (-62°C), can be collected by low-temperature condensation. Concentrations of radon-222 are low; therefore, the vapor pressure of radon-222 will be less than the saturation vapor pressure until the temperature is reduced below the air condensation point. Thus, cryogenic removal of radon-222 from air requires that the radon-222-laden air be liquefied and stored until the radon-222 has decayed.

Several cryogenic methods for removing radon-222 gas have been suggested. In the Little report (Li75), two designs were proposed for a radon-222 liquefier that would allow the radon-222 to decay as a liquid in the reboiler or sparging condenser:

1) Liquefying all input air before it enters the reboiler, where the oxygen and nitrogen are continuously boiled away, leaving behind the liquid radon-222.

or

2) Compressing the input air and allowing it to enter a pool of previously liquefied air as fine bubbles, where the radon-222 condenses and boils away. This method is estimated to be at least 99 percent effective.

Costs. The estimated cost for the second method was \$18 per pound of U_3O_8 produced (1975 dollars) (Li75). Inflated to 1984 dollars, the cost would be \$32 per pound of U_3O_8 or \$122 per ton of ore mined. The application cited was for in-mine control and 50 percent operation, as opposed to full-time operation required for control of mine ventilation exhaust.

Applicability. Although cryogenic methods present no apparent unusual engineering difficulties (since equipment for the liquefaction process is readily available), this approach has not been attempted and it is unlikely that this technique would be practical or cost-effective.

6.2.3 Separation

Semipermeable Membrane Separation

The industrial use of membrane separation has increased substantially in recent years--particularly with respect to separation of helium and hydrogen from other gases. Successful application of membrane separation depends on optimization of the ratio of permeabilities between the gas to be separated by passing through the membrane and those that are to remain in the original stream. The usual approach is to operate the system at relatively high pressures and somewhat elevated temperatures.

The Little report suggests a multiple-stage system designed to concentrate 90 percent of the radon-222 in 10 percent of the air flow (Li75). The Little design for a $2.36\text{-m}^3/\text{s}$ (5000-scfm) unit uses a seven-stage cascade system consisting of 440 m^2 (4728 ft^2) of membrane in the first stage and 651 m^2 (7000 ft^2) in subsequent stages, and it assumes air can be pressurized to 60 atmospheres.

Costs. Estimated costs of this design (in 1975 dollars) are \$61 per pound of U_3O_8 (Li75). Inflated to 1984 dollars, the estimated cost would be \$109 per pound of U_3O_8 or \$420 per ton of ore mined. This cost estimate was based on in-mine control, two shifts a day, 260 days a year; therefore, it is lower than would be required for a surface site and continuous operation on total mine exhaust.

Applicability. The membrane areas and pressures required for this method of radon-222 removal would be difficult to achieve in a mine application. Also, all particulate matter in the gas stream would have to be removed from the system inlet stream to prevent blinding of the membrane surface. Most important, such a system concentrates the radon-222 in a waste stream, which would have to be stored, or cleaned before its release to the environment. Thus, semipermeable membranes do not appear to be a practical control technology for mine exhausts.

Gas Centrifuge Separation

Separation of gases by the use of a centrifuge depends on the mass difference between the gases being separated. The mass differences between radon-222 and the major components of air (oxygen and nitrogen) are seven and eight times, respectively. These sizeable differences suggest that large separations of radon-222 from other exhaust air components would be possible at reasonable peripheral speeds; however, substantial difficulties are involved in utilizing gas centrifuge technology as a practical means of radon-222 control.

In their report (Li75), A. D. Little analyzed this technology and concluded that... "the engineering feasibility of the technique appears to be beyond the reach of the present industrial and technological capability..." They estimated the costs to be about $500,000 per pound of U_3O_8 (1975 dollars). Inflated to 1984 dollars, the estimated cost becomes $890,000 per pound of U_3O_8, or $3.4 million per ton of ore mined.

6.2.4 Absorption

Oxidation/Absorption

Radon-222, although a noble gas, is not completely inert and reacts with strong oxidizing agents such as bromine trifluoride (BrF_3) and dioxygenyl hexafluoroantimonate (O_2SbF_6). The concept of using these agents to convert radon-222 to another form that can be absorbed in a scrubber or on an absorption bed has been investigated by Argonne National Laboratory. Kown et al. (Ko80) summarized their findings:

- Liquid oxidant bromine trifluoride is very effective in oxidizing radon-222 from contaminated mine air. The reaction product of radon-222 is a nonvolatile ionic compound and a liquid scrubber may be used to react radon-222 with the oxidant; however, the oxidant is very corrosive, toxic, and unstable, especially in the presence of water vapor. The scrubber will probably have to be made of corrosion-resistant material, and the air will have to be dehumidified before scrubbing to minimize the oxidant consumption.
- Solid oxidant (O_2SbF_6) reacts rapidly with radon-222 gas and forms a nonvolatile radon-222 compound; hence, it can be used for purification of radon-222-contaminated mine air by use of the absorption bed concept. In the presence of moisture, however, the oxidant is highly corrosive, toxic, and unstable; therefore, the absorption system will have to be made of a special corrosion-resistant material, and the contaminated air will have to be dehumidified before treatment.
- These concepts are still in the laboratory-investigation stage. Many more laboratory tests and pilot plant investigations are necessary to determine chemical consumption, side reactions,

reaction products, handling property of the reactants and product, types of equipment, equipment construction materials, and design parameters.

Costs. No control costs have been estimated for these conceptual systems; however, A. D. Little (Li75) did project costs for the use of molecular sieves to remove the water in the inlet stream to overcome the problem of chemical reagent consumption by reaction with water. Estimated cost (1984 dollars) of the water-removal system was \$66 per pound of U_3O_8 or \$254 per ton of ore mined.

Applicability. Although the concept of radon-222 removal by reaction with a strong oxidant appears technically feasible, the corrosive and toxic nature of reactants and their instability in the presence of moisture make this approach questionable from both a practical and economic standpoint.

Solvent Absorption

Radon-222 is known to be more soluble in some organic solvents than the major gaseous constituents in the air are; therefore, it would appear that an effective scrubber system could be developed that would selectively remove radon-222 from mine air. Problems with various scrubber fluids (their volatility, toxicity, and/or flammability) have been identified (Li75). This report suggested dichlorodifluoromethane (Cl_2CF_2) (Fluorocarbon 12) as a possible solvent for this purpose, and the Oak Ridge Gaseous Diffusion Plant has used Cl_2CF_2 in a 15-scfm pilot-scale scrubber to capture radon-222 and other radioactive noble gases. This compound is a gas at normal conditions; therefore, operation must be at low temperatures or high pressures. (The Oak Ridge system operates at 100 to 600 psi and -45° to 25°C.) With respect to a suitable solvent, Hopke et al. recommends a systematic study of radon-222 solubility in organic solvents to identify an effective and acceptable scrubber system, and suggests perfluorohydrocarbons as candidate compounds for meeting the criteria of low toxicity, flammability, and vapor pressure (Ho84).

Costs. The Little report (Li75) cites an estimated cost (adjusted for inflation to 1984 dollars) of \$189 per pound of U_3O_8 or \$728 per ton of ore mined for organic liquid absorption.

Applicability. Although absorption by scrubbing may ultimately become a technically feasible method, the lack of a suitable solvent limits its possible use. If appropriate solvents are identified, other problems (such as handling of radon-222-contaminated solvent and its purification) must be addressed during the development of a practical industrial-scale system.

6.2.5 Other Possible Methods

A hybrid system that combines the use of semipermeable membranes and organic fluids presents some possible advantages. In such a system, the radon-222 exiting through the membrane would dissolve into the fluid as it passed through to the other side and would be carried away for disposal. The Little report showed relatively high temperatures (98°C) to enhance permeability and the use of toluene, a toxic, flammable liquid (Li75). Costs were estimated to be \$105 per pound of U_3O_8 or \$404 per ton of ore mined (1984 dollars). In addition to the high costs, the problem of identifying a safe, efficient solvent makes such a system unattractive.

Several other systems combining adsorption, absorption, separation, and cryogenic principles can be envisioned, but none offers promise for development of a practical and economically acceptable system for radon-222 removal from large-volume airstreams.

6.2.6 Summary

The chemical inertness of radon-222 makes the development of control measures for mine exhaust application extremely difficult. The low-level radon-222 concentrations and the large air volumes to be treated further compound the difficulty, as does the presence of moisture and other contaminants.

None of the radon-222 control technologies discussed have yet been applied or appear ready to be applied to mine exhaust. In general, the technologies are conceptual in nature, in an early developmental phase, or in the laboratory-investigation stage. Uncertainties now exist regarding their applicability and effectiveness, and additional development is required before these techniques will be ready for either pilot demonstration study or actual full-scale application. In some cases, laboratory tests and/or pilot study investigations are needed to determine what kinds of equipment, construction materials, and design parameters are needed. In other instances, development must await studies to identify suitable collection media; to determine chemical consumption, side reactions, and reaction products; and to examine methods of handling and disposing of chemicals, reactants, byproducts, and the radon-222-bearing concentrate captured by the systems. Table 6-1 summarizes the control techniques discussed in this section.

Considering the current developmental status, their questionable utility, and the high costs associated with their installation and operation, the technologies do not merit further consideration as practical radon-222 control measures for total mine exhausts at this time.

6.3 Methods for Preventing Radon-222 From Entering the Mine Ventilation Air

The two measures for preventing radon-222 from entering the mine ventilation air are 1) preventing diffusion of radon-222 from the ore surface to mine atmosphere, and 2) containing the diffused radon-222 in a confined air space until it has decayed into less active products. The first entails the application of sealant coatings over the exposed ore

Table 6-1. Summary of possible control techniques for radon-222 emissions in mine ventilation exhausts

Radon removal method	Approximate control cost per ton of ore mined, 1984 $	Remarks (current status, major limitations, etc.)
Adsorption systems		
Activated carbon	71-77	Practical engineering constraint limits application to cleaning flows that can reasonably be pulled through a carbon bed.
Molecular sieves	392	Requires development of a molecular sieve that preferentially adsorbs radon over other atmospheric species (O_2, N_2, H_2O, etc.). Activated carbon is currently superior to existing molecular sieves.
Cryogenic condensation	122	Liquefied radon-air mixture must be stored until radon-222 has decayed.
Separation systems		
Semipermeable membranes	420	Radon-222-concentrated waste air must be stored or treated before release.
Gas centrifuge	3.4×10^6	Beyond current industrial/technological capability.
Absorption		
Oxidation absorption	>254	Laboratory-investigation stage and bench-scale studies only. Requires further development, tests, pilot demonstration.
Solvent absorption	728	Suitable solvent with low toxicity, low flammability, low vapor pressure must be found.
Hybrid system		
Semipermeable membrane and organic fluid	404	Solvent handling/purification problem, suitable liquid required, and solvent storage/treatment required to dispose of radon-222 by decay or other means.

surface to form a gas-tight seal to inhibit radon-222 emanation, backfilling of worked-out areas to reduce the exposed surface area, or overpressurization to limit radon-222 emanation. The second involves bulkheading mined-out areas to contain the radon-222.

6.3.1 Sealants

A few field tests have been conducted to evaluate the effectiveness of different sealant materials in underground mines (Fr81a, Ha75). The exposed ore and rock surfaces have many small fissures that allow faster movement of radon-222 gas. Therefore, radon-222 can be prevented from entering the mine air by applying a sealant over the exposed surfaces to close these fissures and pore spaces. A three-coat system of selected materials (a base coat of shotcrete followed by HydrEpoxy 156 and then HydrEpoxy 300) was found to be effective in reducing radon-222 emissions by 50 to 70 percent (Fr81a).

Although the use of sealants has the potential for partial control of radon-222 in uranium mines, this approach is not practiced extensively. Development of sealants and field testing has been conducted in recent years, but the application of sealants is limited to certain areas of the mine, partly because of the effort involved in applying the sealants to the ribs and back of a drift.

For adequate radon-222 control, sealants must provide an impermeable boundary between the surface of the ore body and the mine atmosphere. Heavy wire mesh is used to prevent rock falls in the drifts, and the shotcrete must first be applied over the wire before a coating of sealant is applied. This approach effectively stops the diffusion of radon-222 into the mine ventilation system. The radon-222 gas is retained on the ore body side of the sealant, where it decays into its solid daughter products.

Development and exploration drifts through the ore body can be major sources of radon-222 and are well suited for coating with a sealant. The sealants are used on the entire surface of the drifts. Dirt or other material can be placed on the floor to protect the sealant. In the room-and-pillar stope mining method, most of the drifts driven during the stope development stage are mined out (destroyed) during pillar extraction; thus, the life of the sealant (and radon-222 control) is limited to the time between stope development and mining, which ranges between 6 and 9 months at many mines.

Sometimes the haulage drifts are driven into the barren rock formation under the ore body rather than into the ore body itself, and the ribs and backs of such drifts have very low radon-222 fluxes. Depending on the type of rock and the presence of any residual radon-222 emissions, areas such as intake airways, shops, lunch rooms, etc. are good candidates for sealing. These areas must already have some means of reducing radon-222 concentrations for worker exposure purposes. Also, the areas are basically permanent structures; therefore, the control afforded by sealing them is more long lasting than that produced by applying sealant in the active portions of a mine.

Potential Effectiveness

Uranium ore deposits appear erratically in nature. For this reason, each mine has a unique layout and mining plan and its own mining methods. The characteristics of the radon-222 sources and emissions at each mine also are different. Thus, the specific application of a control technology must be considered separately for each mine. For evaluation of control technologies, however, Kown et al. (Ko80) considered a reference mine with modified room and pillar stoping and a production rate of 1,000 tons of uranium ore per day. Seventy-five percent of the drifts driven during the development of the stopes were assumed to be sealed with a three-layer application of coatings (shotcrete, HydrEpoxy 156, and HydrEpoxy 300). The combination of these three coatings was estimated to be 60 percent effective in the sealing of the surfaces to which they were applied.

The Spokane Research Center of the U.S. Bureau of Mines performed a screening study on 65 coating materials for potential use in underground uranium mines (Fr81a). These materials were first screened for toxicity, flammability, and the ability to reduce radon-222 emanation and then some were actually used during several field tests. Several other tests on sealants were carried out by Lawrence Livermore Laboratories (Ha75). The findings of these investigations are summarized below:

- Under carefully controlled laboratory conditions, many sealants have extremely low permeation coefficients that theoretically will provide a better than 100:1 attenuation of radon-222. The presence of so-called pinholes, however, and the difficulty of applying a perfect coating on an irregular ore surface reduce the effectiveness of these sealants considerably.

- Field tests suggest that water-based epoxies such as HydrEpoxy 156 and HydrEpoxy 300 are well suited for the underground mine application. A three coat system (a base coating of shotcrete followed by HydrEpoxy 156 and then HydrEpoxy 300) was found to effectively reduce radon-222 by 50 to 75 percent. The shotcrete is needed to eliminate cracks and to provide a better base for the sealants.

- The amount of sealants used varies considerably among different mines.

- The amount of exposed ore surface (radon-222 source) that can be coated with a sealant is limited. Drifts through the ore body, which are major radon-222 sources, are best suited for sealant coating. Most of the drifts in a modern uranium mine, however, are destroyed as the mining progresses. In a room-and-pillar stope mine, for example, most drifts driven during the stope development stage are mined out (destroyed) during pillar extraction. The sealant coating applied to these drifts will thus have a limited life.

Cost of Sealant Coating

Information was derived from the application of sealant to 49,200 m^2 (530,000 ft^2) of drift surfaces annually at the following rate of application (Ko80):

Shotcrete -	0.909 gal/ft^2
HydrEpoxy 156 -	0.018 gal/ft^2
HydrEpoxy 300 -	0.032 gal/ft^2

Other reported estimates of sealant usage in different mines are (Fr78a):

Shotcrete -	0.5 to 3.0 gal/ft^2 at \$0.25/gal
HydrEpoxy 156 -	0.008 to 0.026 gal/ft^2 at \$7.36/gal
HydrEpoxy 300 -	0.019 to 0.047 gal/ft^2 at \$6.40/gal

The annual costs developed by Kown et al. were \$344,300 (\$0.66/ft^2) or \$1.45 per ton of ore removed. These costs are based on an average life of 8 months for the sealant and a 60 percent reduction of radon-222 emissions. Cost estimates of other sealants range from \$0.30 to \$1.10/ft^2 (Fr81a).

Pacific Northwest Laboratory's recent study of 13 mines indicates an average cost of \$5.80 per ton of ore mined (\$0.34/ft^2) if 80 percent of the surface is sealed (B184). The Bureau of Mines states that intake airways, shops, lunchrooms, and any areas where radon-222 emanation rates are high are candidates for the use of sealants (Fr79).

Sealant effectiveness is based on many assumptions and approximations. In one study, the estimated radon-222 emissions from an unsealed ore surface were assumed to be 55 pCi/ft^2-s or 4.75 x 10^{-6} Ci/ft^2/day (Ko80). Based on an average sealant life of 8 months and 60 percent reduction of radon, the use of sealant was assumed to reduce the radon-222 emanation from active stopes by 23 percent. This reduction (1.01 Ci/day) represented 11 percent of the radon-222 emissions from the entire mine. The use of a sealant life of 8 months was a conservative estimate, and it is expected that actual sealant life will be much longer.

The active stopes would not be completely sealed. The intake airways into the stopes could be sealed, but not the drifts into the stopes. Mines that are developed completely in the ore zone could seal the drifts as they advance toward the back of the mine to help provide cleaner air throughout the mine and reduce emissions to the surface. Under these conditions, the life of the sealant would be greater than 8 months.

Thus, the use of sealants as a radon-222 control measure has limited application and can be considered only one component of an overall control strategy. A sealant program would have to be part of a careful mining plan so the coating activity would not interfere with ongoing mining activity or expose mine workers to a new group of materials that evolve during sealant curing.

6.3.2 Backfilling

Description of Technique

Backfilling involves the filling of a worked-out stope with waste material brought down into the area from the surface. To fill as much of the stope as possible (usually only 80 percent of the volume can be filled), filling takes place at the highest accessible point in the stope (Fr81b). The material used in backfilling, typically the sand fraction of the classified mill tailings greater than 200 mesh, is conveyed to the stope in a slurry.

The current practice of backfilling of worked-out areas in an underground mine is for the purpose of ground support and stabilization. This practice can be expensive; therefore, it is applied primarily when the cave-in of mined-out areas would cause the surface above the stope to subside. If no surface subsidence is expected, the mined-out stopes are allowed to cave in without backfilling.

Backfilling usually occurs only after the required grade of the uranium ore has been removed from a part of the mine and the mine operator has no plans to go back into the same stope for further excavations. As a result, the technique is not practiced at mines that use drift expansion as the primary means of ore exploration. At those mines where backfilling is practiced, an 80 percent reduction in the volume of the stopes is normally achieved. A secondary benefit of backfilling can be a reduction in the overall radon-222 emissions from the area. Still another benefit (to the mine operator) is a reduction in power consumption, as the area no longer needs to be ventilated (Fr81a).

A study by the Bureau of Mines and Kerr-McGee Nuclear to determine how effective backfilling mill tailings into the mine stopes is in the reduction of radon-222 emissions indicated a net radon-222 reduction of 84 percent from the stope (Fr81b). The study was based on the results of backfilling only one stope in a mine. Battelle Pacific Northwest Laboratories estimated an efficiency of 80 percent if classified mill tailings and a layer of clean surface sands are used for backfilling (B184). The average cost estimated by PNL was $12.64 per ton of ore mined.

6.3.3 Bulkheads

Bulkheading of mined-out areas is a common practice among mine operators. Bulkheads are simple air-restraining barriers used to direct airflow to the work place and to isolate worked-out areas from active areas. This practice reduces radon-222 and decay product concentration in the active areas of the mine and also reduces the volume of air needed to ventilate the mine. The bulkheads currently used in underground uranium mines are intended for in-mine control of radon-222 decay product concentrations and are not always airtight. The numerous different designs range from brick and mortar to plywood.

Even though decay of the radon-222 is occurring behind the bulkhead, the radon-222 flux of the enclosed area is of such a magnitude that an equilibrium concentration is quickly attained (see Appendix C). The concentration of radon-222 behind the bulkhead has been reported to be anywhere from 30,000 (Li82) to 300,000 pCi/liter (Fr78b). In some mines, the radon-222 contained by the bulkhead will leak out of the sealed area through the rock itself when the pressure in the sealed area exceeds the pressure in the passageway. This leakage must be controlled to prevent contamination of the fresh air. This can be accomplished with a simple passive bleed vent leading to an exhaust airway in order to balance the pressures between the enclosed area and the active portion, or a bleed vent connected to an exhaust fan to create a lower pressure behind the bulkhead with respect to the active area. The air bleed must be an exhaust airway. In lieu of an air bleed, the mine operator must rely strictly on the integrity of the bulkhead to minimize any leakage. This may or may not be effective, depending on the permeation of radon-222 through the host rock. A vent system under negative pressure ensures that any air leakage that occurs is into the contaminated area rather than into the active mining area. Bulkheads installed for reducing radon-222 emissions to the atmosphere, as opposed to those installed to prevent radon-222 emissions into the active mining areas, must be constructed with a tight seal (to reduce leakage). Bulkheads constructed for this purpose are shown in Figures 6-1 and 6-2.

The volume of a mine that is bulkheaded depends on several factors, including the age of the mine, the layout of the ventilation system, the mine layout, and the ore exploration methods. The volume of worked-out areas in newly opened mines is small, which limits the fraction of the mine that can be sealed. In some mines, the worked-out areas become the exhaust airways as the mining process retreats toward the intake airways. In this case the major portion of the worked-out area must be kept open to allow the passage of air to the exhaust vent. Some of the stopes from the main mine areas can be bulkheaded, but the main volume of worked-out areas is kept open. In this type of mine layout, only limited portions of the inactive areas can be bulkheaded unless new exhaust vents or drifts are constructed to reduce the need for inactive mine areas to be used as exhaust passages.

Inspection of bulkheads in inactive mined-out areas is not always feasible because these areas are subject to rock-falls and cave-ins. Leakage of bulkheads in these inactive areas does not always affect mine air quality, as the mine ventilation flows toward the exhaust; however, such leakage can increas the radon-222 exhausted to the atmosphere. If an inaccessible bulkhead starts to leak and affect an active area (as determined from increased radon-222 levels), another bulkhead or series of bulkheads may have to be built to contain this portion of the mine.

Exploration methods also have an impact on radon-222 exposure reduction methods in use. Some mine drifts are constantly being expanded for exploration purposes rather than being abandoned and sealed. This is a practice at some mines in the Colorado Plateau area. Temporary bulkheads would be required in such mines, along with some means of ventilating the inactive area before removing the bulkhead for additional exploration.

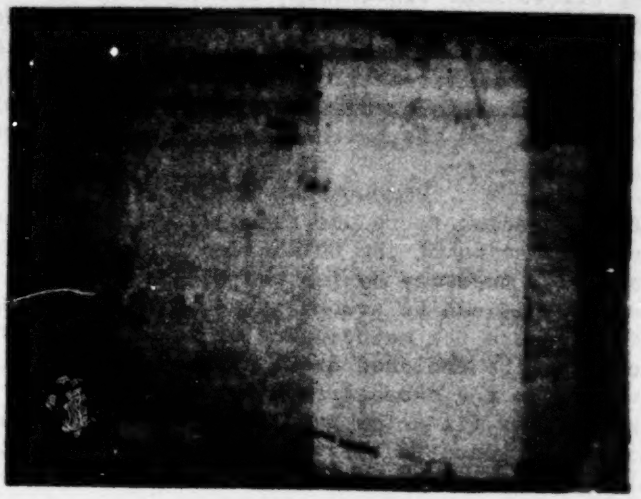

Figure 6-1. Example plywood bulkhead with plastic liner (Li82).

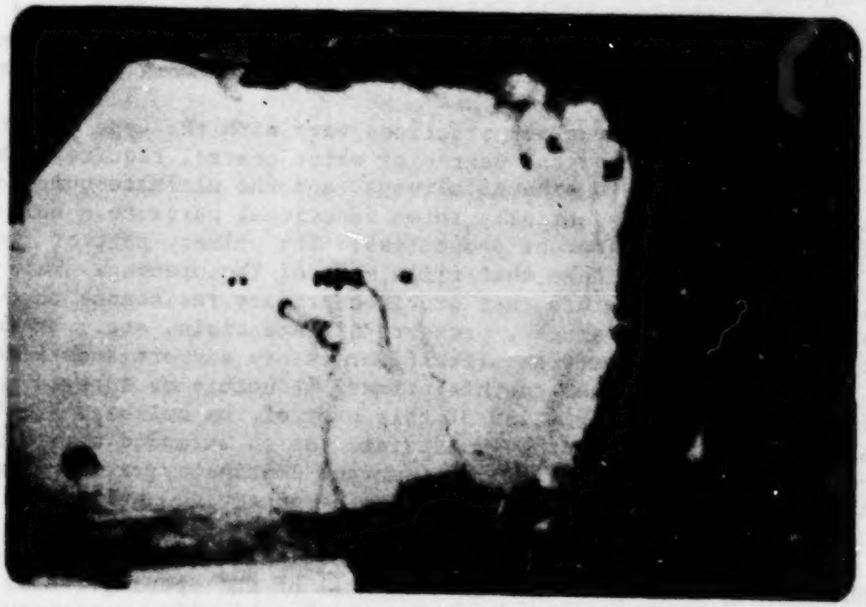

Figure 6-2. Example bulkhead with coating (Li82).

Bulkheading allows mine ventilation air rates to be reduced while maintaining acceptable radon-222 decay product levels. Radon-222 will continue to emanate into the closed-off area and possibly leak into the active area as a result of barometric pressure changes, blasting shock waves, and the like. Therefore, an adequate air flow out of the enclosed area must be maintained and the bulkheaded area must be kept under negative pressure.

The use of bulkheading to reduce radon-222 emissions to the atmosphere requires ventilation of the bulkheaded area at a rate low enough to allow the radon-222 to decay behind the bulkhead before it is released to the atmosphere. This can be accomplished by constructing a tightly sealed bulkhead to ensure the maintenance of negative pressure with a minimum air flow from the enclosed area. Equilibrium conditions tend to cause the air vented to the exhaust from a bulkheaded area to have high radon-222 concentrations (in a low gas flow). Thus, a point will be reached at which an increase in the ventilation rate from the bulkheaded area will result in no actual radon-222 emission reduction.

Technical Considerations

An important consideration that must be made in the implementation of a bulkheading program is that of miner safety. Any activity conducted in an underground mine, as well as materials used underground, must conform with existing MSHA regulations for protection of the underground work force. These regulations will necessarily impact the design, construction, and use of bulkheads in the underground mine work environment.

Current bulkhead construction practices vary with the type of rock in which the mine is located, the degree of water control required, the proximity of the bulkhead to exhaust airways, and the ultimate purpose of the bulkhead. There are essentially three functional parts to a bulkhead, and each requires different properties. The primary part of the bulkhead is the basic structure that fills most of the opening. This can be a relatively rigid structure that provides primary resistance to mechanical abuse, blasting shocks, pressure differentials, etc. It may be a continuous nonporous membrane itself, or it may support such a membrane (which might be attached to this primary structure or sprayed onto it). The important characteristics of this part of the bulkhead are 1) structural strength, which must be maintained for an extended period in the mine-operating environment; and 2) membrane continuity, i.e., it must not crack or develop holes or leaks in the mine operating environment.

The second part of the bulkhead is the portion that forms the seal between the primary structure and the rock wall of the opening. This part, which is relatively narrow, is supported by the primary structure; therefore, limited structural strength is required. Nevertheless, this portion must provide a positive seal that can be maintained through blasting shock waves, rock movement, running water, and other adverse conditions of the mine operating environment.

The third part of the bulkhead is the surface sealing of the rock for a distance of approximately 1 meter (3 feet) from the plane of the bulkhead to minimize migration of the radon-222 around the bulkhead through the rock. This seal must be of a material that will adhere to and seal the surface of the rock even if it is damp. Positive sealing of the rock surface must be maintained through normal movement of the rock, blasting, water influx, and other conditions that are part of mine operations.

All the air in sealed-off areas is free to move quite rapidly in response to small pressure gradients; therefore, bulkhead leaks that permit escape of the trapped air at only relatively slow rates (i.e., a few cubic feet per minute) can easily increase radon-222 decay product concentrations in the air of adjacent areas to unacceptable levels over periods of hours, or even a few days. Chronic effects have been observed in periods of repeatedly cycling barometric pressures and in situations where large reservoirs of trapped (and highly radon-222-polluted) air communicate, through leaky bulkheads and other routes, with relatively small volumes of ventilation air (Mu82).

Some relief of positive-air-pressure conditions in sealed-off mine areas can be achieved by simply opening a low-resistance air passage or bleed vent between the bulkheaded area and a convenient exhaust airway. A passive bleeder, however, can be only partially effective in overcoming an environmentally (or artificially) induced pressure differential; therefore, imperfectly sealed bulkheads may still leak to some extent under the influence of the remaining pressure difference.

Several methods have been used to reduce the amount of uncontrolled leakage into or out of an enclosed area and to limit the flow of the bleedstream. Several researchers have found it necessary to apply sealants to the ribs and back of the bulkheaded drift to limit permeation of radon-222 around the bulkhead (Li82, Fr78b). A differential pressure transducer has also been used to monitor the pressure differential across a bulkhead (Li82). The transducer provides a signal to control the operation of a forced-convection fan and thereby ensures that the desired negative pressure differential is maintained.

Safe disposal of the exhaust air from a sealed-off inactive area can present some problems, especially if the polluted air cannot be exhausted directly into an isolated vent airway. The use of large-diameter vent tubing of flexible fabric or plastic is not considered safe for conducting polluted exhaust air through occupied portions of the mine. This kind of air conduit is best operated under positive pressure; therefore, such a system would be exposed to the possibility of leaks, which would result in contamination of the air around it. For operation under negative pressure, the exhaust vent tube must be made of some rigid material, e.g., metal, fiberglass-reinforced plastic, or wire-wound plastic. Rigid air conduits are not impractical, but neither are they widely used in underground mines, largely because they cost more and are more susceptible to damage than flexible tubing.

Bleedstream cleanup with activated carbon has been suggested as an alternative to its direct release to the atmosphere (Bl84, Li82, Ko80).

This alternative may be able to provide an additional 95 to 99 percent reduction in the radon-222 emission from the bleedstream (Ko80, B184). Such a unit would obviously add cost and complexity to a radon-222 emission control program, and such a system has not yet been demonstrated under actual mine conditions.

Effectiveness

The success of a bulkheading program to reduce radon-222 emissions depends upon the mine operator building well-constructed bulkheads, performing regular inspections to ensure no damages have occurred, and maintaining only a slight negative pressure in the sealed area.

The ability to achieve negative pressure in bulkheaded areas with a minimum bleedstream flow is affected by the following factors:

- Bulkhead sealant failure
- Formation of cracks in the bulkhead/rock interface
- The presence of fissures or longholes in the bulkheaded area
- Flow around the bulkhead due to high permeability related to the porosity of the host rock

Any of these conditions can cause the pressure in the bulkheaded area to equilibrate with the pressure in the active mining area. This will require a higher flow rate out of the enclosed area to maintain a negative pressure differential and will reduce the radon-222 emission reduction potential.

Theoretical calculations were made to illustrate the effectiveness of bulkheading in reducing radon-222 emissions. These calculations involved modeling the radon-222 decaying in a mine area sealed with a bulkhead. The model used a drift with a surface area of 66,890 m^2 (720,000 ft^2), releasing radon-222 into a volume of 59,450 m^3 (2,100,000 ft^3). For these calculations a constant radon-222 flux rate of 9.29 pCi/ft^2 per second was used. The model does not take into account some important factors, such as barometric pressure changes or declining concentration gradient, which occur as the quantity of radon-222 increases. Therefore, the results obtained from this model represent the upper boundary limits.

The results of these calculations are reported in Appendix C for radon-222 concentrations (pCi/liter) in the sealed area, daily radon-222 decay (Ci), daily radon-222 removal (Ci), and the percent radon-222 decay in the sealed area. The amount of radon-222 decay is a measure of the emission reduction.

Four air removal rates are analyzed; there are percentages of total volume of air in the sealed area which is removed per day. For a 10 percent removal rate, approximately 150 cfm is removed from the sealed area. The following is a summary of the results of these calculations at steady state:

Air removal rate (%)	Estimated radon decay (%)
0*	100
10	64
20	47
50	26

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*In practice, a zero percent removal rate cannot usually be achieved because a completely tight bulkhead is difficult to construct. Air is removed to maintain negative pressure.

Bulkhead Costs

The cost components of a basic bulkhead consist of materials and labor for the construction of the bulkhead, the cost involved with monitoring and producing a negative-pressure differential, and labor and maintenance for periodic maintenance and testing. Table 6-2 presents estimated 1984 costs of these components. Assuming that any given volume of a mine can be isolated with 10 bulkheads (B184) and that some components of the bulkhead will require reconstruction every 6 months (worst case), a bulkhead program yields an annual control cost of approximately $41,000.

Table 6-2. Cost of components of bulkhead construction (1984 dollars)

Item	Labor[(a)]	Materials	Total
Preparation			
Site selection and measurement	30	0	30
Precut material and transport	60	0	60
Construction			
Framing			
8 in. x 8 in. - 5 at 10 ft	60	140	200
2 in. x 6 in. - 4 at 16 ft	15	23	38
Plywood - 6 sheets at ½ in.	150	102	252
Surface cleaning	45	0	45
Grout			
Floor - 4 sacks of cement	75	20	95
Ribs and back - 3 bags of plaster	60	27	87
Urethane bead - 3 gallons	30	50	80
Membrane (Aquafas) - 44 gallons	90	400	490
Cleanup	45	0	45
Subtotal	660	762	1422
Vent duct (fiberglass) - 500 ft	60	1000	1060
Fan - ¼ hp, 375 cfm	15	195	210
Total	735	1957	2692

(a) Based on $15/h including overhead and fringe benefits.

Activated Carbon System on Air Bleedstream

Application of an activated carbon system for bleedstream radon-222 control entails an additional cost component. Detailed capital and annual operating cost estimates for an activated carbon system to treat a 0.047-m^3/s (100-cfm) bleedstream vent flow are provided in Appendix D. These estimates indicate that a single activated carbon system will result in an annual cost ranging between $67,000 and $85,000. Assuming that one such system will be required for each of the 10 bulkheads, the addition of bleedstream control will increase the annual cost of a bulkhead program by $670,000 to $850,000. Although a credit is expected for reduced ventilation air requirements, no credit is taken because of current practices. It is also assumed that existing bulkheads would require reconstruction; therefore, no credit is taken for existing bulkheads.

In conclusion, although bulkheads have the potential to reduce radon-222 emissions, such reductions are achievable only with careful attention to bulkheading practices. Based on the considerations presented in this section, the cost of a program in the reference mine would be $0.37 per ton of ore mined. Additional control afforded by continuous activated carbon adsorption of the bleedstream would increase the cost substantially by $6 to $7.60 per ton of ore.

6.3.4 Mine Pressurization for Radon-222 Control

Positive mine pressurization has been tried several times to force the radon-222 in the mine atmosphere back into the walls of the mine. One researcher found no effect from exhausting vs. blowing ventilation (Th81). In general, these efforts have been successful in reducing the radon-222 concentrations in the mine itself. An "air" sink is necessary to accept the radon-222. If the radon-222 is forced through the ore body or surrounding area to the surface, it can decay before coming to the surface. If the area is impermeable, however, radon-222 will return to its previous levels. In tests by the Bureau of Mines, the radon-222 levels in the mine were reduced by 20 percent (releases to the atmosphere were not determined). The surrounding soil must be permeable enough to hold radon-222 and allow for its decay, but not so permeable so as to allow significant increases in surface emissions. In a recent EPA report, it was concluded that positive-pressure ventilation was not effective in reducing atmospheric emissions of radon-222 (EPA84). Another researcher found that although an immediate radon-222 reduction is obtained as a result of overpressurization, the radon-222 flux soon returns to levels observed prior to application of mine pressure (Sc66).

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APPENDIX A

LIST OF UNDERGROUND URANIUM MINES

OPERATING AND CLOSED UNDERGROUND URANIUM MINES, 1984 (DOL84)

State	Company name and address	Mine name	County	Status(a)
Arizona	Energy Fuels Nuclear, Inc. P.O. Box 36 Fredonia, AZ 86022	Kanab North	Mohave	Permanentaly closed 7/84(b)
		Hacks Canyon 2	Mohave	Active (14 employees)(c)(d)
		Hacks Canyon 1	Mohave	Permanently closed 8/84
		Pigeon	Coconino	Active (25 employees)(d)
Colorado	Phil Bunker 1092 Montana St. Nucla, CO 81422	Mineral Joe No. 2	Montrose	Permanently closed 7/84
	Cleghorn Mining Co. P.O. Box 2604 Grand Junction, CO 81502	Rex 38	Montrose	Permanently closed 3/84
	Cotter Corp. 9305 W. Alameda Pky. Lakewood, CO 80226	Schwartzwalder	Jefferson	Active (152 employees)(d)
	Cotter Corp. P.O. Box 700 Nucla, CO 81424	C-CM-25	Montrose	Temporarily closed 8/84
		C-SR-13A	Montrose	Temporarily closed 8/84
		C-LP-2	Montrose	Temporarily closed 8/84
		C-JD-7	Montrose	Temporarily closed 7/84
		C-JD-9	Montrose	Temporarily closed 4/84
		C-SM-18	Montrose	Temporarily closed 8/84
		C-LP-22A	Montrose	Temporarily closed 8/84
	Robert M. Hurst Mining P.O. Box 238 Dove Creek, CO 81324	Black Jack Summit	San Miguel	Permanently closed 3/84

State	Company name and address	Mine name	County	Status[a]
Colorado (cont.)	Jones Mining Co. P.O. Box 32 Bedrock, CO 81411	JB4	Montrose	Permanently closed 3/84
	Kelmine Corp. P.O. Box 272 Naturita, CO 81422	C-JD-6	Montrose	Temporarily closed 7/84
	Kelmine Corp. P.O. Box 1383 Moab, UT 84532	Duggan Adit	Montrose	Temporarily closed 8/83
	Minerals Recovery Corp. 2801 Youngfield No. 221 Golden, CO 80401	Pickett Corral Sun Cup Dolores River Centennial Horseshoe	Montrose San Miguel San Miguel San Miguel San Miguel	Temporarily closed 1/84 Temporarily closed 1/84 Temporarily closed 1/84 Active (9 employees)[d] Temporarily closed 1/84
	Rajah Ventures, Ltd. P.O. Box 2360 Grand Junction, CO 81522	October Pack Rat	Mesa Mesa	Permanently closed 3/84 Temporarily closed 4/84
	Sage & Sage Mining P.O. Box 323 Naturita, CO 81422	Betty Jean	Montrose	Permanently closed 7/84
	UMETCO Minerals Corp. P.O. Box 508 Dove Creek, CO 81324	Dermo-Snyder	San Miguel	Temporarily closed 8/84
New Mexico	Bokum Res. Corp. P.O. Box 13958 Albuquerque, NM 87192	Marquez	McKinley	Temporarily closed 2/84
	Cobb Resources Corp. 313 Washington, SE Albuquerque, NM 87108	Section 12	McKinley	Temporarily closed 4/83

State	Company name and address	Mine name	County	Status[a]
New Mexico (cont.)	Gulf Mineral Resources Co. P.O. Box 1150 Grants, NM 87020	Mt. Taylor	Cibola	Temporarily closed 3/84
	Homestake Mining Co. P.O. Box 98 Grants, NM 87020	Section 23[e]	McKinley	Active (169 employees)[d]
		Section 25[f]	McKinley	Temporarily closed 11/83
		Section 13	McKinley	Temporarily closed 10/81
	Phillips Uranium Corp. P.O. Box J Crownpoint, NM 87313	Nose Rock No. 1	McKinley	Temporarily closed 6/83
	Quivera Mining Co. P.O. Box 218 Grants, NM 87020	Section 17[f]	McKinley	Active (12 employees)
		Section 19[e]	McKinley	Active (63 employees)
		Church Rock No. 1	McKinley	Active (48 employees)
		Section 24[e]	McKinley	Active (12 employees)
		Section 30[e]	McKinley	Active (76 employees)
		Section 30 West[e]	McKinley	Active (59 employees)
		Section 33[f]	McKinley	Active (12 employees)
		Section 35[e]	McKinley	Active (102 employees)
		Section 36	McKinley	Active (81 employees)
	Sohio Western Mining Co. P.O. Box 25201 Albuquerque, NM 87125	L-Bar	Valencia	Active (18 employees)
	Todilto Explor. & Dev. 3810 Academy Parkway, S. Albuquerque, NM 87109	No. 2 - Piedra Triste	McKinley	Permanently closed 6/84
	UNC Mining & Milling P.O. Drawer QQ Gallup, NM 87301	Ann Lee[f]	McKinley	Temporarily closed 6/83
		NE Church Rock[e]	McKinley	Temporarily closed 3/83
		Sandstone[f]	McKinley	Temporarily closed 6/83
		St. Anthony	Valencia	Permanently closed 12/83
		Old Church Rock	McKinley	Temporarily closed 6/83

State	Company name and address	Mine name	County	Status[a]
New Mexico (cont.)	Western Nuclear, Inc. P.O. Box 899 Thoreau, NM 87323	Ruby Nos. 3 & 4	McKinley	Active (31 employees)
Utah	Atlas Minerals P.O. Box 1207 Moab, UT 84532	Pandora Rim Velvet	San Juan San Juan San Juan	Temporarily closed 3/84 Temporarily closed 3/84 Temporarily closed 3/84
	Ronald E. Beck 4451 E. Easy Street Moab, UT 84532	Pappy No. 1	Grand	Permanently closed 6/84
	Cleghorn Mining Co. P.O. Box 2604 Grand Junction, CO 81502	Blue Cap	San Juan	Active (7 employees)
	Cotter Corp. 9305 W. Alameda Pky. Lakewood, CO 80226	Bi-Centennial	Grand	Active (8 employees)
	Cotter Corp. P.O. Box 700 Nucla, CO 81424	Thornburg Memorial	Grand	Active
	Energy Fuels, Nuc., Inc. P.O. Box 59 Green River, UT 84525	Sahara	Emery	Temporarily closed 8/81
	Garth Noyes Tickaboo, UT 84734	Trackyte No. 5	Garfield	Temporarily closed 1/84
	Homestake Mining Co. 1726 Cole Blvd. Golden, CO 80401	LaSal No. 2	San Juan	Permanently closed 8/84

State	Company name and address	Mine name	County	Status[(a)]
Utah (cont.)	Kelmine Corp. P.O. Box 1383 Moab, UT 84532	Cub	San Juan	Permanently closed 6/84
	Pene Mining Co. P.O. Box 16 Thompson, UT 84540	Little Eva	Grand	Permanently closed 4/84
	Plateau Resources, Ltd. P.O. Box 511 Tickaboo, UT 84734	Lucky Strike	Garfield	Active (26 employees)
	Rio Algom Corp. P.O. Box 610 Moab, UT 84532	Lisbon	San Juan	Active (63 employees)[(d)]
	Rio Algom Corp. P.O. Box 619 Moab, UT 84532	Mivida	San Juan	Active (14 employees)
	Shumway Mining P.O. Box 443 Moab, UT 84532	Monte Cristo	Grand	Permanently closed 7/84
	Glen A. Shumway P.O. Box 322 Blanding, UT 84511	Strawberry	San Juan	Permanently closed 3/84
	T&J Mining 371 Wingate Moab, UT 84532	Red Vanadium	Grand	Permanently closed 2/84
	T.S.&R., Inc. 2125 Canyonlands Moab, UT 84532	Redrock	San Juan	Permanently closed 2/84

State	Company name and address	Mine name	County	Status(a)
	UMETCO Minerals Corp. P.O. Box 1049 Grand Junction, CO 81501	Wilson Silverbell LaSal Hecla Shaft	San Juan San Juan San Juan	Temporarily closed 3/84 Temporarily closed 3/84 Temporarily closed 3/84
	Union Carbide P.O. Box 1029 Grand Junction, CO 81501	Snowball	San Juan	Permanently closed 4/84
	Utah Mineral Dev. 350 Park Rd. Moab, UT 84532	Bandit	San Juan	Permanently closed 6/84
	Western Key Enterprise, Inc. 3080 E. Spanish Trail Moab, UT 84532	Geo No. 1	Montrose	Temporarily closed 4/83
Wyoming	Pathfinder Mines Corp. P.O. Box 831 Riverton, WY 82501	Lucky Mc 7B Four Corners	Fremont Fremont	Active (5 employees) Active (6 employees)
	Silver King Mines, Inc. P.O. Box 560 Casper, WY 82601	Golden Eagle	Converse	Active (24 employees)
	Western Nuclear, Inc. Jeffrey City, WY 82310	Sheep Mountain	Fremont	Active (21 employees)

(a) Status of underground uranium mines as of October 1984.

(b) Date indicates when mine was closed.

(c) Number of employees at active underground uranium mines.

(d) Mines still active in March 1985.

(e) Production supplemented by mine-water recovery (NM83, NM84).

(f) Production from mine-water recovery only (NM83, NM84).

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APPENDIX B

CALCULATIONS OF RADON-222 CONCENTRATIONS IN AIR AT SELECTED DISTANCES FROM REFERENCE MINE AND CASE STUDY MINES

Table B-1. Industrial source complex long-term modeling results for reference underground uranium mine, modeled with plume rise

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MODELSP.LST;4                    15-JAN-1985 10:07                 Page 1

**** ISCLT ************* Model Mine with Plume Rise, Stack Releases (MODELSP.SOR)                        ******** PAGE      1 ****

*** WARNING - FREQ. OF OCCURRENCE OF SPD VS. DIR IS NOT 1.0 FOR SEASON  1, PROG. DIVIDES BY   5.11400 TO NORMALIZE
                                   - ISCLT INPUT DATA -

          NUMBER OF SOURCES =    5
          NUMBER OF X AXIS GRID SYSTEM POINTS =   15
          NUMBER OF Y AXIS GRID SYSTEM POINTS =   16
          NUMBER OF SPECIAL POINTS =     0
          NUMBER OF SEASONS =   1
          NUMBER OF WIND SPEED CLASSES =    6
          NUMBER OF STABILITY CLASSES =    6
          NUMBER OF WIND DIRECTION CLASSES =  16
          FILE NUMBER OF DATA FILE USED FOR REPORTS =    1
          THE PROGRAM IS RUN IN RURAL MODE
          CONCENTRATION (DEPOSITION) UNITS CONVERSION FACTOR =0.31709999E+02
          ACCELERATION OF GRAVITY (METERS/SEC**2) =  9.800
          HEIGHT OF MEASUREMENT OF WIND SPEED (METERS) =   7.000
          ENTRAINMENT PARAMETER FOR UNSTABLE CONDITIONS = 0.600
          ENTRAINMENT PARAMETER FOR STABLE CONDITIONS = 0.600
          CORRECTION ANGLE FOR GRID SYSTEM VERSUS DIRECTION DATA NORTH (DEGREES) =   0.000
          DECAY COEFFICIENT =0.00000000E+00
          PROGRAM OPTION SWITCHES = 1, 2, 1, 0, 0, 3, 2, 2, 3, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0,
          ALL SOURCES ARE USED TO FORM SOURCE COMBINATION  1
           RANGE X AXIS GRID SYSTEM POINTS (METERS )=     200.00,      500.00,     1000.00,     2000.00,     3000.00,     4000.00,
              5000.00,     7000.00,     8000.00,     9000.00,    10000.00,    15000.00,    20000.00,    30000.00,    50000.00,
       AZIMUTH BEARING Y AXIS GRID SYSTEM POINTS (DEGREES)=       0.00,       22.50,       45.00,       67.50,       90.00,      112.50,
               135.00,      157.50,      180.00,      202.50,      225.00,      247.50,      270.00,      292.50,      315.00,      337.50,

                         - AMBIENT AIR TEMPERATURE (DEGREES KELVIN) -

                   STABILITY  STABILITY  STABILITY  STABILITY  STABILITY  STABILITY
                   CATEGORY 1 CATEGORY 2 CATEGORY 3 CATEGORY 4 CATEGORY 5 CATEGORY 6
          SEASON  1   296.8300   286.8300   286.8300   286.8300   286.8300   286.8300

                              - MIXING LAYER HEIGHT (METERS) -

                                         SEASON 1
                        WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                        CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
       STABILITY CATEGORY 10.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
       STABILITY CATEGORY 20.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
       STABILITY CATEGORY 30.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
       STABILITY CATEGORY 40.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
       STABILITY CATEGORY 50.100000E+050.100000E+050.100000E+050.100000E+050.100000E+050.100000E+05
       STABILITY CATEGORY 60.100000E+050.100000E+050.100000E+050.100000E+050.100000E+050.100000E+05
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Table B-1 (cont.)

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MODELSP.LST;4            15-JAN-1985 10:07          Page 2
**** ISCLT ************ Model Mine with Plume Rise, Stack Releases (MODELSP.SOR)                    ******** PAGE     2 ****
                              - ISCLT INPUT DATA (CONT.) -

               - FREQUENCY OF OCCURRENCE OF WIND SPEED, DIRECTION AND STABILITY -

                                        SEASON 1

                                  STABILITY CATEGORY 1

              WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED
              CATEGORY 1   CATEGORY 2   CATEGORY 3   CATEGORY 4   CATEGORY 5   CATEGORY 6
 DIRECTION   ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
 (DEGREES)
     0.000    0.00039108   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
    22.500    0.00039108   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
    45.000    0.00000000   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
    67.500    0.00000000   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
    90.000    0.00019554   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
   112.500    0.00000000   0.00019554   0.00000000   0.00000000   0.00000000   0.00000000
   135.000    0.00019554   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
   157.500    0.00058663   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
   180.000    0.00097771   0.00039108   0.00000000   0.00000000   0.00000000   0.00000000
   202.500    0.00078217   0.00078217   0.00000000   0.00000000   0.00000000   0.00000000
   225.000    0.00078217   0.00097771   0.00000000   0.00000000   0.00000000   0.00000000
   247.500    0.00234650   0.00078217   0.00000000   0.00000000   0.00000000   0.00000000
   270.000    0.00039108   0.00136879   0.00000000   0.00000000   0.00000000   0.00000000
   292.500    0.00078217   0.00019554   0.00000000   0.00000000   0.00000000   0.00000000
   315.000    0.00019554   0.00117325   0.00000000   0.00000000   0.00000000   0.00000000
   337.500    0.00058663   0.00019554   0.00000000   0.00000000   0.00000000   0.00000000

                                        SEASON 1

                                  STABILITY CATEGORY 2

              WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED
              CATEGORY 1   CATEGORY 2   CATEGORY 3   CATEGORY 4   CATEGORY 5   CATEGORY 6
 DIRECTION   ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
 (DEGREES)
     0.000    0.00039108   0.00097771   0.00000000   0.00000000   0.00000000   0.00000000
    22.500    0.00058663   0.00058663   0.00019554   0.00000000   0.00000000   0.00000000
    45.000    0.00039108   0.00039108   0.00019554   0.00000000   0.00000000   0.00000000
    67.500    0.00000000   0.00058663   0.00000000   0.00000000   0.00000000   0.00000000
    90.000    0.00000000   0.00019554   0.00000000   0.00000000   0.00000000   0.00000000
   112.500    0.00019554   0.00000000   0.00000000   0.00000000   0.00000000   0.00000000
   135.000    0.00058663   0.00019554   0.00000000   0.00000000   0.00000000   0.00000000
   157.500    0.00175988   0.00039108   0.00019554   0.00000000   0.00000000   0.00000000
   180.000    0.00234650   0.00195542   0.00000000   0.00000000   0.00000000   0.00000000
   202.500    0.00136879   0.00215096   0.00039108   0.00000000   0.00000000   0.00000000
   225.000    0.00078217   0.00078217   0.00039108   0.00019554   0.00000000   0.00000000
   247.500    0.00097771   0.00175988   0.00019554   0.00000000   0.00000000   0.00000000
   270.000    0.00097771   0.00117325   0.00019554   0.00000000   0.00000000   0.00000000
   292.500    0.00117325   0.00097771   0.00000000   0.00000000   0.00000000   0.00000000
   315.000    0.00078217   0.00254204   0.00000000   0.00000000   0.00000000   0.00000000
   337.500    0.00078217   0.00156433   0.00000000   0.00000000   0.00000000   0.00000000
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Table B-1 (cont.)

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MODEL6P.LST;8                 15-JAN-1985 10:07             Page 3

**** ISCLT ************  Model Mine with Plume Rise, Stack Releases (MODEL6P.SOR)                          ******** PAGE     3 ****

                                  - ISCLT INPUT DATA (CONT.) -

                    - FREQUENCY OF OCCURRENCE OF WIND SPEED, DIRECTION AND STABILITY -

                                           SEASON 1

                                     STABILITY CATEGORY 3

                 WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                 CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   DIRECTION    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
   (DEGREES)
      0.000      0.00019554  0.00215096  0.00117325  0.00000000  0.00000000  0.00000000
     22.500      0.00058663  0.00039108  0.00019554  0.00000000  0.00000000  0.00000000
     45.000      0.00000000  0.00097771  0.00000000  0.00000000  0.00000000  0.00000000
     67.500      0.00019554  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
     90.000      0.00019554  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
    112.500      0.00078217  0.00078217  0.00000000  0.00000000  0.00000000  0.00000000
    135.000      0.00117325  0.00039108  0.00000000  0.00000000  0.00000000  0.00000000
    157.500      0.00234650  0.00234650  0.00000000  0.00000000  0.00000000  0.00000000
    180.000      0.00449746  0.00391083  0.00078217  0.00000000  0.00000000  0.00000000
    202.500      0.00195542  0.00332421  0.00293313  0.00000000  0.00000000  0.00000000
    225.000      0.00195542  0.00175988  0.00078217  0.00019554  0.00000000  0.00000000
    247.500      0.00136879  0.00195542  0.00312867  0.00058663  0.00000000  0.00000000
    270.000      0.00332421  0.00371529  0.00234650  0.00078217  0.00000000  0.00000000
    292.500      0.00156433  0.00410638  0.00039108  0.00000000  0.00000000  0.00000000
    315.000      0.00195542  0.00215096  0.00215096  0.00000000  0.00000000  0.00000000
    337.500      0.00039108  0.00215096  0.00195542  0.00019554  0.00000000  0.00000000

                                           SEASON 1

                                     STABILITY CATEGORY 4

                 WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                 CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   DIRECTION    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
   (DEGREES)
      0.000      0.00879938  0.00664842  0.00195542  0.00039108  0.00000000  0.00000000
     22.500      0.00488854  0.00117325  0.00058663  0.00019554  0.00000000  0.00000000
     45.000      0.00547517  0.00117325  0.00058663  0.00000000  0.00000000  0.00000000
     67.500      0.00449746  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
     90.000      0.00684396  0.00019554  0.00019554  0.00000000  0.00000000  0.00000000
    112.500      0.00469300  0.00136879  0.00039108  0.00019554  0.00000000  0.00000000
    135.000      0.00684396  0.00293313  0.00156433  0.00000000  0.00000000  0.00000000
    157.500      0.00469300  0.00273758  0.00117325  0.00019554  0.00000000  0.00000000
    180.000      0.00547517  0.00625734  0.00488854  0.00175988  0.00000000  0.00000000
    202.500      0.00410638  0.00567071  0.00645288  0.00097771  0.00019554  0.00000000
    225.000      0.00449746  0.00234650  0.00567071  0.00371529  0.00117325  0.00000000
    247.500      0.00312867  0.00351975  0.00547517  0.00645288  0.00058663  0.00000000
    270.000      0.00410638  0.00449746  0.00762613  0.00743058  0.00097771  0.00000000
    292.500      0.00273758  0.00469300  0.00527963  0.00332421  0.00039108  0.00000000
    315.000      0.00586625  0.00371529  0.00547517  0.00215096  0.00000000  0.00000000
    337.500      0.01036371  0.00684396  0.00547517  0.00097771  0.00019554  0.00000000
```

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Table B-1 (cont.)

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MODELSP.LST;4                15-JAN-1985 10:07              Page 4
**** ISCLT ************  Model Mine with Plume Rise, Stack Releases (MODELSP.80R)                          ******** PAGE     6 ****
                                         - ISCLT INPUT DATA (CONT.) -

                        - FREQUENCY OF OCCURRENCE OF WIND SPEED, DIRECTION AND STABILITY -
                                                   SEASON 1
                                            STABILITY CATEGORY 5
               WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED
 DIRECTION     CATEGORY 1   CATEGORY 2   CATEGORY 3   CATEGORY 4   CATEGORY 5   CATEGORY 6
(DEGREES)    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.0000MPS)( 9.5000MPS)(12.5000MPS)
     0.000   0.01055925   0.01055925   0.00332421   0.00097771   0.00000000   0.00000000
    22.500   0.01857646   0.00606179   0.00097771   0.00019554   0.00000000   0.00000000
    45.000   0.01251467   0.00234650   0.00078217   0.00019554   0.00000000   0.00000000
    67.500   0.01114590   0.00117325   0.00058663   0.00078217   0.00000000   0.00000000
    90.000   0.01564334   0.00254204   0.00058663   0.00000000   0.00000000   0.00000000
   112.500   0.00830929   0.00449746   0.00234650   0.00058663   0.00000000   0.00000000
   135.000   0.00821275   0.00586625   0.00136879   0.00019554   0.00019554   0.00000000
   157.500   0.00762613   0.00391083   0.00136879   0.00039108   0.00019554   0.00000000
   180.000   0.00762613   0.00645288   0.00508408   0.00273758   0.00019554   0.00000000
   202.500   0.00371529   0.00782167   0.00743058   0.00449746   0.00078217   0.00000000
   225.000   0.00508930   0.00449746   0.00488854   0.00293313   0.00039108   0.00000000
   247.500   0.00449746   0.00508408   0.00527963   0.00723504   0.00175988   0.00000000
   270.000   0.00762613   0.00919046   0.01075479   0.01134142   0.00332421   0.00000000
   292.500   0.00547517   0.00469309   0.00527963   0.00430192   0.00215096   0.00000000
   315.000   0.01368792   0.00645288   0.00488854   0.00567071   0.00117325   0.00019554
   337.500   0.01916309   0.01603442   0.00684396   0.00215096   0.00019554   0.00000000
                                                   SEASON 1
                                            STABILITY CATEGORY 6
               WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED   WIND SPEED
 DIRECTION     CATEGORY 1   CATEGORY 2   CATEGORY 3   CATEGORY 4   CATEGORY 5   CATEGORY 6
(DEGREES)    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.0000MPS)( 9.5000MPS)(12.5000MPS)
     0.000   0.00703950   0.01407909   0.00136879   0.00000000   0.00000000   0.00000000
    22.500   0.02170513   0.02072742   0.00195542   0.00000000   0.00000000   0.00000000
    45.000   0.01271021   0.00332421   0.00078217   0.00000000   0.00019554   0.00000000
    67.500   0.00371529   0.00117325   0.00039108   0.00039108   0.00000000   0.00000000
    90.000   0.00762613   0.00097771   0.00039108   0.00039108   0.00000000   0.00000000
   112.500   0.00312867   0.00312867   0.00156433   0.00097771   0.00000000   0.00000000
   135.000   0.00430192   0.00410638   0.00136879   0.00039108   0.00000000   0.00000000
   157.500   0.00293313   0.00117325   0.00136879   0.00097771   0.00019554   0.00000000
   180.000   0.00293313   0.00821275   0.00586625   0.00136879   0.00019554   0.00000000
   202.500   0.00215096   0.00625734   0.00625734   0.00136879   0.00000000   0.00000000
   225.000   0.00234650   0.00351975   0.00391083   0.00117325   0.00019554   0.00000000
   247.500   0.00254204   0.00449746   0.00527963   0.00273758   0.00000000   0.00000000
   270.000   0.00606179   0.00938600   0.01173250   0.00527963   0.00117325   0.00000000
   292.500   0.00195542   0.00488854   0.00606179   0.00215096   0.00019554   0.00000000
   315.000   0.00312867   0.00684396   0.00430192   0.00332421   0.00097771   0.00019554
   337.500   0.01916017   0.01192904   0.00762613   0.00175988   0.00058663   0.00019554
```

Table B-1 (cont.)

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MODELSP.LST;0                 15-JAN-1985 10:07              Page 5
**** ISCLT ************* Model Mine with Plume Rise, Stack Releases (MODELSP.SOR)                                ******** PAGE    5 ****
                                             - ISCLT INPUT DATA (CONT.) -

                               - VERTICAL POTENTIAL TEMPERATURE GRADIENT (DEGREES KELVIN/METER) -

                      WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                      CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
STABILITY CATEGORY 10.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 20.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 30.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 40.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 50.200000E-010.200000E-010.200000E-010.200000E-010.200000E-010.200000E-01
STABILITY CATEGORY 60.350000E-010.350000E-010.350000E-010.350000E-010.350000E-010.350000E-01

                                     - WIND PROFILE POWER LAW EXPONENTS -

                      WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                      CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
STABILITY CATEGORY 10.100000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 20.150000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 30.200000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 40.250000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 50.300000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 60.300000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
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Table B-1 (cont.)

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MODELSP.LST;1                    15-JAN-1985 10:07                 Page 6

**** ISCLT *************  Model Mine with Plume Rise, Stack Releases (MODELSP.SOP)                                        ******** PAGE     6 ****

                                              - SOURCE INPUT DATA -

C T SOURCE SOURCE      X           Y        EMISSION  BASE /
A A NUMBER  TYPE   COORDINATE  COORDINATE   HEIGHT   ELEV- /                  - SOURCE DETAILS DEPENDING ON TYPE -
R P                    (M)         (M)        (M)    ATION /
D E                                                   (M)  /
-------------------------------------------------------------------------------------------------------------------------------------
X        1  STACK       -28.00     -106.00    1.00     0.00 GAS EXIT TEMP (DEG K)= 286.03, GAS EXIT VEL. (M/SEC)= 16.20,
                                                             STACK DIAMETER (M)= 1.510, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (CURIES / YEAR / 80 METER                  ) -
                                                                         SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                       2.20000E+03
WARNING - DISTANCE BETWEEN SOURCE        1 AND POINT X,Y=     200.00,      100.00 IS LESS THAN PERMITTED
WARNING - DISTANCE BETWEEN SOURCE        1 AND POINT X,Y=     200.00,      202.50 IS LESS THAN PERMITTED
X        2  STACK       322.00      184.00    1.00     0.00 GAS EXIT TEMP (DEG K)= 286.03, GAS EXIT VEL. (M/SEC)= 16.20,
                                                             STACK DIAMETER (M)= 1.510, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (CURIES / YEAR / 80 METER                  ) -
                                                                         SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                       2.20000E+03
X        3  STACK      -202.00      460.00    1.00     0.00 GAS EXIT TEMP (DEG K)= 286.03, GAS EXIT VEL. (M/SEC)= 16.20,
                                                             STACK DIAMETER (M)= 1.510, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (CURIES / YEAR / 80 METER                  ) -
                                                                         SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                       2.20000E+03
WARNING - DISTANCE BETWEEN SOURCE        3 AND POINT X,Y=     500.00,      337.50 IS LESS THAN PERMITTED
X        4  STACK       543.00     -400.00    1.00     0.00 GAS EXIT TEMP (DEG K)= 286.03, GAS EXIT VEL. (M/SEC)= 16.20,
                                                             STACK DIAMETER (M)= 1.510, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (CURIES / YEAR / 80 METER                  ) -
                                                                         SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                       2.20000E+03
X        5  STACK      -177.00     -695.00    1.00     0.00 GAS EXIT TEMP (DEG K)= 286.03, GAS EXIT VEL. (M/SEC)= 16.20,
                                                             STACK DIAMETER (M)= 1.510, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (CURIES / YEAR / 80 METER                  ) -
                                                                         SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                       2.20000E+03
```

Table B-1 (cont.)

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MODELSP.LST;8                 15-JAN-1985 10:07                  Page 7
**** ISCLT ************  Model Mine with Plume Rise, Stack Releases (MODELSP.SOR)                        ******** PAGE    7 ****

   **   ANNUAL GROUND LEVEL CONCENTRATION (PICO CURIES / LITER                   ) FROM ALL SOURCES COMBINED           **
                                               - GRID SYSTEM RECEPTORS -
                                             - X AXIS (RANGE    , METERS) -
              200.000      500.000      1000.000     2000.000     3000.000     4000.000     5000.000     7000.000     8000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                   - CONCENTRATION -
          ------------------------------------------------------------------------------------------------------------------
   337.500    0.226067     0.130081     0.133513     0.091629     0.067367     0.051307     0.040546     0.027600     0.023495
   315.000    0.171911     0.106700     0.103467     0.090232     0.072776     0.058008     0.047132     0.033100     0.028458
   292.500    0.150176     0.090937     0.083900     0.085416     0.068402     0.053684     0.043055     0.029695     0.025358
   270.000    0.143610     0.080410     0.077067     0.086092     0.078287     0.066395     0.055956     0.040980     0.035669
   247.500    0.146902     0.080633     0.076830     0.079010     0.067077     0.053799     0.043557     0.030293     0.025913
   225.000    0.158988     0.094114     0.085329     0.098163     0.091284     0.077572     0.065375     0.047921     0.041740
   202.500    0.171323     0.142589     0.118022     0.166924     0.160458     0.137142     0.115743     0.084973     0.074088
   180.000    0.187630     0.224979     0.231287     0.191138     0.147036     0.112912     0.089239     0.060507     0.051398
   157.500    0.240370     0.280694     0.273520     0.234230     0.107487     0.140016     0.119181     0.082694     0.070783
   135.000    0.296309     0.275335     0.357653     0.191560     0.135090     0.100510     0.078122     0.052003     0.043933
   112.500    0.339240     0.330650     0.303598     0.180376     0.109223     0.075346     0.056064     0.035538     0.029582
    90.000    0.300711     0.397259     0.299373     0.196419     0.139953     0.105105     0.082570     0.055927     0.047580
    67.500    0.265275     0.375351     0.298232     0.143916     0.093286     0.066737     0.050869     0.033226     0.027937
    45.000    0.260926     0.321093     0.252209     0.123962     0.080855     0.058487     0.044967     0.029702     0.025061
    22.500    0.252772     0.346377     0.246150     0.144399     0.095792     0.069052     0.052813     0.034594     0.029109
     0.000    0.267436     0.329452     0.219195     0.144496     0.103149     0.077455     0.060744     0.041000     0.034032

                                               - GRID SYSTEM RECEPTORS -
                                             - X AXIS (RANGE    , METERS) -
             9000.000    10000.000    15000.000    20000.000    30000.000    50000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                   - CONCENTRATION -
          ------------------------------------------------------------------------------------------------------------------
   337.500    0.020318     0.017805     0.019599     0.007291     0.004333     0.002268
   315.000    0.024776     0.021961     0.013245     0.009104     0.005404     0.002977
   292.500    0.021975     0.019296     0.011515     0.007920     0.004696     0.002449
   270.000    0.031353     0.027305     0.017299     0.012125     0.007333     0.003848
   247.500    0.022479     0.019740     0.011797     0.009100     0.004795     0.002495
   225.000    0.036750     0.032692     0.020369     0.014355     0.008733     0.004671
   202.500    0.065315     0.058147     0.036305     0.025730     0.015732     0.008466
   180.000    0.049363     0.039809     0.022940     0.015733     0.009201     0.004820
   157.500    0.061473     0.054050     0.032074     0.022437     0.013366     0.007009
   135.000    0.037759     0.032912     0.019253     0.013116     0.007709     0.003995
   112.500    0.025139     0.021717     0.012377     0.008395     0.004856     0.002502
    90.000    0.041145     0.036058     0.021499     0.010664     0.006980     0.004083
    67.500    0.023933     0.020815     0.012124     0.008270     0.004971     0.002537
    45.000    0.021526     0.018759     0.010987     0.007504     0.004420     0.002297
    22.500    0.024049     0.021705     0.012646     0.008628     0.005079     0.002642
     0.000    0.030079     0.026331     0.015631     0.010773     0.006413     0.003369
```

Table B-2. Industrial source complex long-term modeling results for reference underground uranium mine, modeled without plume rise

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MODELAP.LST;3                 15-JAN-1985 10:06              Page 1

**** ISCLT *************  Model Mine with No Plume Rise, Ground Level Area Releases (MODELAP.BOM)          ******** PAGE      1 ****

*** WARNING - FREQ. OF OCCURRENCE OF SPD VS. DIR IS NOT 1.0 FOR SEASON  1, PROB. DIVIDED BY   5.11400 TO NORMALIZE
                                    - ISCLT INPUT DATA -

          NUMBER OF SOURCES =   5
          NUMBER OF X AXIS GRID SYSTEM POINTS =   15
          NUMBER OF Y AXIS GRID SYSTEM POINTS =   16
          NUMBER OF SPECIAL POINTS =    0
          NUMBER OF SEASONS =   1
          NUMBER OF WIND SPEED CLASSES =   6
          NUMBER OF STABILITY CLASSES =   6
          NUMBER OF WIND DIRECTION CLASSES =  16
          FILE NUMBER OF DATA FILE USED FOR REPORTS =   1
          THE PROGRAM IS RUN IN RURAL MODE
          CONCENTRATION (DEPOSITION) UNITS CONVERSION FACTOR =0.31709999E+02
          ACCELERATION OF GRAVITY (METERS/SEC**2) =  9.000
          HEIGHT OF MEASUREMENT OF WIND SPEED (METERS) =   7.000
          ENTRAINMENT PARAMETER FOR UNSTABLE CONDITIONS = 0.600
          ENTRAINMENT PARAMETER FOR STABLE CONDITIONS = 0.600
          CORRECTION ANGLE FOR GRID SYSTEM VERSUS DIRECTION DATA NORTH (DEGREES) =   0.000
          DECAY COEFFICIENT =0.00000000E+00
          PROGRAM OPTION SWITCHES = 1, 2, 1, 0, 0, 3, 2, 2, 3, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0,
          ALL SOURCES ARE USED TO FORM SOURCE COMBINATION   1
           RANGE X AXIS GRID SYSTEM POINTS (METERS )=      200.00,       500.00,      1000.00,      2000.00,      3000.00,      4000.00,
              5000.00,     7000.00,     8000.00,     9000.00,    10000.00,    15000.00,    20000.00,    30000.00,    50000.00,
   AZIMUTH BEARING Y AXIS GRID SYSTEM POINTS (DEGREES)=       0.00,        22.50,        45.00,        67.50,        90.00,       112.50,
           135.00,      157.50,      180.00,      202.50,      225.00,      247.50,      270.00,      292.50,      315.00,      337.50,

                          - AMBIENT AIR TEMPERATURE (DEGREES KELVIN) -

                 STABILITY  STABILITY  STABILITY  STABILITY  STABILITY  STABILITY
                 CATEGORY 1 CATEGORY 2 CATEGORY 3 CATEGORY 4 CATEGORY 5 CATEGORY 6
       SEASON  1   285.9300   286.0300   286.0300   286.0300   286.0300   286.0300

                              - MIXING LAYER HEIGHT (METERS) -

                                         SEASON 1
                  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                  CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   STABILITY CATEGORY 10.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
   STABILITY CATEGORY 20.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
   STABILITY CATEGORY 30.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
   STABILITY CATEGORY 40.100000E+040.100000E+040.100000E+040.100000E+040.100000E+040.100000E+04
   STABILITY CATEGORY 50.100000E+050.100000E+050.100000E+050.100000E+050.100000E+050.100000E+05
   STABILITY CATEGORY 60.100000E+050.100000E+050.100000E+050.100000E+050.100000E+050.100000E+05
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Table B-2 (cont.)

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MODELAP.LST;3                 15-JAN-1985 10:06              Page 2
**** ISCLT ************  Model Mine with No Plume Rise, Ground Level Area Release (MODELAP.BOR)          ******** PAGE    2 ****
                                         - ISCLT INPUT DATA (CONT.) -

                          - FREQUENCY OF OCCURRENCE OF WIND SPEED, DIRECTION AND STABILITY -
                                                   SEASON 1
                                             STABILITY CATEGORY 1
                 WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                 CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   DIRECTION    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
   (DEGREES)
       0.000     0.00039108  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
      22.500     0.00039108  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
      45.000     0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
      67.500     0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
      90.000     0.00019554  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
     112.500     0.00000000  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
     135.000     0.00019554  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
     157.500     0.00058663  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
     180.000     0.00097771  0.00039108  0.00000000  0.00000000  0.00000000  0.00000000
     202.500     0.00078217  0.00078217  0.00000000  0.00000000  0.00000000  0.00000000
     225.000     0.00078217  0.00097771  0.00000000  0.00000000  0.00000000  0.00000000
     247.500     0.00234650  0.00078217  0.00000000  0.00000000  0.00000000  0.00000000
     270.000     0.00039108  0.00136879  0.00000000  0.00000000  0.00000000  0.00000000
     292.500     0.00078217  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
     315.000     0.00019554  0.00117325  0.00000000  0.00000000  0.00000000  0.00000000
     337.500     0.00058663  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
                                                   SEASON 1
                                             STABILITY CATEGORY 2
                 WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                 CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   DIRECTION    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
   (DEGREES)
       0.000     0.00039108  0.00097771  0.00000000  0.00000000  0.00000000  0.00000000
      22.500     0.00058663  0.00058663  0.00019554  0.00000000  0.00000000  0.00000000
      45.000     0.00039108  0.00039108  0.00019554  0.00000000  0.00000000  0.00000000
      67.500     0.00000000  0.00058663  0.00000000  0.00000000  0.00000000  0.00000000
      90.000     0.00000000  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
     112.500     0.00019554  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
     135.000     0.00058663  0.00019554  0.00000000  0.00000000  0.00000000  0.00000000
     157.500     0.00175988  0.00039108  0.00019554  0.00000000  0.00000000  0.00000000
     180.000     0.00234650  0.00195542  0.00000000  0.00000000  0.00000000  0.00000000
     202.500     0.00136879  0.00215096  0.00039108  0.00000000  0.00000000  0.00000000
     225.000     0.00078217  0.00078217  0.00039108  0.00019554  0.00000000  0.00000000
     247.500     0.00097771  0.00175988  0.00019554  0.00000000  0.00000000  0.00000000
     270.000     0.00097771  0.00117325  0.00019554  0.00000000  0.00000000  0.00000000
     292.500     0.00117325  0.00097771  0.00000000  0.00000000  0.00000000  0.00000000
     315.000     0.00078217  0.00254204  0.00000000  0.00000000  0.00000000  0.00000000
     337.500     0.00078217  0.00156433  0.00000000  0.00000000  0.00000000  0.00000000
```

Table B-2 (cont.)

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MODELAP.LST;3              15-JAN-1985 10:06              Page 3
**** ISCLT ************* Model Mine with No Plume Rise, Ground Level Area Release (MODELAP.BOR)          ******** PAGE     3 ****
                                   - ISCLT INPUT DATA (CONT.) -

                   - FREQUENCY OF OCCURRENCE OF WIND SPEED, DIRECTION AND STABILITY -
                                            SEASON 1

                                      STABILITY CATEGORY 3
                WIND SPEED    WIND SPEED    WIND SPEED    WIND SPEED    WIND SPEED    WIND SPEED
                CATEGORY 1    CATEGORY 2    CATEGORY 3    CATEGORY 4    CATEGORY 5    CATEGORY 6
 DIRECTION    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
 (DEGREES)
     0.000     0.00019554    0.00215096    0.00117325    0.00000000    0.00000000    0.00000000
    22.500     0.00058663    0.00039108    0.00019554    0.00000000    0.00000000    0.00000000
    45.000     0.00000000    0.00097771    0.00000000    0.00000000    0.00000000    0.00000000
    67.500     0.00019554    0.00019554    0.00000000    0.00000000    0.00000000    0.00000000
    90.000     0.00019554    0.00019554    0.00000000    0.00000000    0.00000000    0.00000000
   112.500     0.00078217    0.00078217    0.00000000    0.00000000    0.00000000    0.00000000
   135.000     0.00117325    0.00039108    0.00000000    0.00000000    0.00000000    0.00000000
   157.500     0.00234650    0.00234650    0.00000000    0.00000000    0.00000000    0.00000000
   180.000     0.00449746    0.00391083    0.00078217    0.00000000    0.00000000    0.00000000
   202.500     0.00195542    0.00332421    0.00293313    0.00000000    0.00000000    0.00000000
   225.000     0.00195542    0.00175988    0.00078217    0.00000000    0.00000000    0.00000000
   247.500     0.00136879    0.00195542    0.00312867    0.00019554    0.00000000    0.00000000
   270.000     0.00332421    0.00371529    0.00234650    0.00058663    0.00000000    0.00000000
   292.500     0.00156433    0.00410638    0.00039108    0.00078217    0.00000000    0.00000000
   315.000     0.00195542    0.00215096    0.00215096    0.00000000    0.00000000    0.00000000
   337.500     0.00039108    0.00215096    0.00195542    0.00019554    0.00000000    0.00000000
                                            SEASON 1

                                      STABILITY CATEGORY 4
                WIND SPEED    WIND SPEED    WIND SPEED    WIND SPEED    WIND SPEED    WIND SPEED
                CATEGORY 1    CATEGORY 2    CATEGORY 3    CATEGORY 4    CATEGORY 5    CATEGORY 6
 DIRECTION    ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
 (DEGREES)
     0.000     0.00879938    0.00664842    0.00195542    0.00039108    0.00000000    0.00000000
    22.500     0.00488856    0.00117325    0.00058663    0.00019554    0.00000000    0.00000000
    45.000     0.00547517    0.00117325    0.00058663    0.00000000    0.00000000    0.00000000
    67.500     0.00449746    0.00000000    0.00000000    0.00000000    0.00000000    0.00000000
    90.000     0.00684396    0.00019554    0.00019554    0.00000000    0.00000000    0.00000000
   112.500     0.00469300    0.00136879    0.00039108    0.00019554    0.00000000    0.00000000
   135.000     0.00684396    0.00293313    0.00156433    0.00000000    0.00000000    0.00000000
   157.500     0.00469300    0.00273758    0.00117325    0.00019554    0.00000000    0.00000000
   180.000     0.00547517    0.00625734    0.00488856    0.00175988    0.00000000    0.00000000
   202.500     0.00410639    0.00567071    0.00645288    0.00097771    0.00019554    0.00000000
   225.000     0.00449756    0.00234650    0.00567071    0.00371529    0.00117325    0.00000000
   247.500     0.00312867    0.00351975    0.00547517    0.00645288    0.00058663    0.00000000
   270.000     0.00410633    0.00449746    0.00762613    0.00743058    0.00097771    0.00000000
   292.500     0.00273758    0.00469300    0.00527963    0.00332421    0.00039108    0.00000000
   315.000     0.00586625    0.00371529    0.00547517    0.00215096    0.00000000    0.00000000
   337.500     0.01036371    0.00684396    0.00547517    0.00097771    0.00019554    0.00000000
```

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Table B-2 (cont.)

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MODELAP.LST;3                15-JAN-1985 10:06              Page 4

**** ISCLT ************  Model Mine with No Plume Rise, Ground Level Area Releases (MODELAP.SOR)           ******** PAGE     4 ****

                                     - ISCLT INPUT DATA (CONT.) -

                      - FREQUENCY OF OCCURRENCE OF WIND SPEED, DIRECTION AND STABILITY -

                                               SEASON 1

                                         STABILITY CATEGORY 5

                  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                  CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   DIRECTION     ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
   (DEGREES)
      0.000       0.01055925  0.01055925  0.00332421  0.00097771  0.00000000  0.00000000
     22.500       0.01857636  0.00606179  0.00097771  0.00019554  0.00000000  0.00000000
     45.000       0.01251467  0.00234650  0.00078217  0.00019554  0.00000000  0.00000000
     67.500       0.01114580  0.00117325  0.00058663  0.00078217  0.00000000  0.00000000
     90.000       0.01564334  0.00254204  0.00058663  0.00000000  0.00000000  0.00000000
    112.500       0.00840829  0.00449746  0.00234650  0.00058663  0.00000000  0.00000000
    135.000       0.00821275  0.00586625  0.00136879  0.00019554  0.00019554  0.00000000
    157.500       0.00762613  0.00391083  0.00136879  0.00039108  0.00019554  0.00000000
    180.000       0.00762613  0.00645288  0.00508400  0.00273758  0.00019554  0.00000000
    202.500       0.00371529  0.00782167  0.00743058  0.00449746  0.00078217  0.00000000
    225.000       0.00508400  0.00449746  0.00488854  0.00293313  0.00039108  0.00000000
    247.500       0.00449746  0.00508400  0.00527963  0.00723504  0.00175988  0.00000000
    270.000       0.00762613  0.00719046  0.01075479  0.01134142  0.00332421  0.00000000
    292.500       0.00547517  0.00469300  0.00527963  0.00430192  0.00215096  0.00019554
    315.000       0.01368792  0.00645288  0.00488854  0.00567071  0.00117325  0.00000000
    337.500       0.01916309  0.01603442  0.00684396  0.00215096  0.00019554  0.00000000

                                               SEASON 1

                                         STABILITY CATEGORY 6

                  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                  CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
   DIRECTION     ( 0.7500MPS)( 2.5000MPS)( 4.3000MPS)( 6.8000MPS)( 9.5000MPS)(12.5000MPS)
   (DEGREES)
      0.000       0.00703950  0.01407900  0.00136879  0.00000000  0.00000000  0.00000000
     22.500       0.02170513  0.02072742  0.00195542  0.00000000  0.00000000  0.00000000
     45.000       0.01271021  0.00332421  0.00078217  0.00000000  0.00019554  0.00000000
     67.500       0.00371529  0.00117325  0.00039108  0.00039108  0.00000000  0.00000000
     90.000       0.00762613  0.00097771  0.00039108  0.00039108  0.00000000  0.00000000
    112.500       0.00312867  0.00312867  0.00156433  0.00097771  0.00000000  0.00000000
    135.000       0.00430192  0.00410638  0.00136879  0.00039108  0.00000000  0.00000000
    157.500       0.00293313  0.00117325  0.00136879  0.00097771  0.00019554  0.00000000
    180.000       0.00293313  0.00821275  0.00586625  0.00136879  0.00019554  0.00000000
    202.500       0.00215096  0.00625734  0.00625734  0.00136879  0.00000000  0.00000000
    225.000       0.00234650  0.00351975  0.00391083  0.00117325  0.00019554  0.00000000
    247.500       0.00254204  0.00449746  0.00527963  0.00273758  0.00000000  0.00000000
    270.000       0.00606179  0.00939600  0.01173250  0.00527963  0.00117325  0.00000000
    292.500       0.00195542  0.00488854  0.00606179  0.00215096  0.00019554  0.00000000
    315.000       0.00312867  0.00684396  0.00430192  0.00332421  0.00097771  0.00019554
    337.500       0.01016817  0.01192504  0.00762613  0.00175988  0.00058663  0.00019554
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Table B-2 (cont.)

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MODELAP.LST;3                   15-JAN-1985 10:06                 Page 5
**** ISCLT ************* Model Mine with No Plume Rise, Ground Level Area Release (MODELAP.BOR)            ******** PAGE      5 ****
                                               - ISCLT INPUT DATA (CONT.) -

                                 - VERTICAL POTENTIAL TEMPERATURE GRADIENT (DEGREES KELVIN/METER) -

                          WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                          CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
STABILITY CATEGORY 10.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 20.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 30.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 40.000000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 50.200000E-010.200000E-010.200000E-010.200000E-010.200000E-010.200000E-01
STABILITY CATEGORY 60.350000E-010.350000E-010.350000E-010.350000E-010.350000E-010.350000E-01

                                          - WIND PROFILE POWER LAW EXPONENTS -

                          WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED  WIND SPEED
                          CATEGORY 1  CATEGORY 2  CATEGORY 3  CATEGORY 4  CATEGORY 5  CATEGORY 6
STABILITY CATEGORY 10.100000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 20.150000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 30.200000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 40.250000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 50.300000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
STABILITY CATEGORY 60.300000E+000.000000E+000.000000E+000.000000E+000.000000E+000.000000E+00
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Table B-2 (cont.)

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MODELAP.LST;3                    15-JAN-1985 10:06              Page 6

**** ISCLT *************  Model Mine with No Plume Rise, Ground Level Area Release (MODELAP.SOR)          ******** PAGE      6 ****

                                        - SOURCE INPUT DATA -

C T SOURCE SOURCE       X           Y       EMISSION  BASE /
A A NUMBER  TYPE   COORDINATE  COORDINATE   HEIGHT   ELEV- /                     - SOURCE DETAILS DEPENDING ON TYPE -
R P                   (M)         (M)         (M)    ATION /
D E                                                   (M)  /
------------------------------------------------------------------------------------------------------------------------------------
X       1  AREA      -28.00     -106.00     1.00     0.00 WIDTH OF AREA (M)=     1.51
                                                            - SOURCE STRENGTHS (CURIES / YEAR / SQ METERPER SQUARE METER) -
                                                                     SEASON 1       SEASON 2      SEASON 3      SEASON 4
                                                                  9.64900E+02
WARNING - DISTANCE BETWEEN SOURCE        1 AND POINT X,Y=     200.00,      180.00 IS LESS THAN PERMITTED
WARNING - DISTANCE BETWEEN SOURCE        1 AND POINT X,Y=     200.00,      202.50 IS LESS THAN PERMITTED
X       2  AREA      322.00      184.00     1.00     0.00 WIDTH OF AREA (M)=     1.51
                                                            - SOURCE STRENGTHS (CURIES / YEAR / SQ METERPER SQUARE METER) -
                                                                     SEASON 1       SEASON 2      SEASON 3      SEASON 4
                                                                  9.64900E+02
X       3  AREA     -292.00      460.00     1.00     0.00 WIDTH OF AREA (M)=     1.51
                                                            - SOURCE STRENGTHS (CURIES / YEAR / SQ METERPER SQUARE METER) -
                                                                     SEASON 1       SEASON 2      SEASON 3      SEASON 4
                                                                  9.64900E+02
WARNING - DISTANCE BETWEEN SOURCE        3 AND POINT X,Y=     500.00,      337.50 IS LESS THAN PERMITTED
X       4  AREA      543.00     -400.00     1.00     0.00 WIDTH OF AREA (M)=     1.51
                                                            - SOURCE STRENGTHS (CURIES / YEAR / SQ METERPER SQUARE METER) -
                                                                     SEASON 1       SEASON 2      SEASON 3      SEASON 4
                                                                  9.64900E+02
X       5  AREA     -170.00     -695.00     1.00     0.00 WIDTH OF AREA (M)=     1.51
                                                            - SOURCE STRENGTHS (CURIES / YEAR / SQ METERPER SQUARE METER) -
                                                                     SEASON 1       SEASON 2      SEASON 3      SEASON 4
                                                                  9.64900E+02
```

Table B-2 (cont.)

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MODELAP.LST;3                    15-JAN-1985 10:06              Page 7

**** ISCLT ************  Model Mine with No Plume Rise, Ground Level Area Releases (MODELAP.80R)          ******** PAGE     7 ****

   **   ANNUAL GROUND LEVEL CONCENTRATION (PICO CURIES / LITER                        ) FROM ALL SOURCES COMBINED            **
                                                    - GRID SYSTEM RECEPTORS -
                                                  - X AXIS (RANGE    , METERS) -
                  200.000      500.000      1000.000      2000.000    3000.000      4000.000      5000.000      7000.000      8000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                            -  CONCENTRATION  -
          -------------------------------------------------------------------------------------------------------------------------
     337.500     8.106980     1.380239     1.193307     0.293082     0.149290     0.094470     0.066036     0.039912     0.032615
     315.000     6.632443     6.667230     1.053580     0.318893     0.171078     0.111453     0.080316     0.049003     0.040331
     292.500     6.085063     3.030773     1.039049     0.322906     0.164029     0.103091     0.073455     0.043796     0.035773
     270.000     6.093034     2.981897     1.007273     0.363694     0.212052     0.142590     0.104551     0.064935     0.053731
     247.500     8.455514     3.092302     1.111706     0.356796     0.189430     0.116747     0.081222     0.047490     0.030540
     225.000    11.869236     3.777282     1.962185     0.521431     0.203471     0.104081     0.132905     0.080905     0.066603
     202.500     3.015293     7.579065     4.315895     0.953392     0.495064     0.320797     0.231079     0.141208     0.116569
     180.000     3.424650     6.049090     4.476326     0.837064     0.379105     0.228130     0.156983     0.090970     0.073690
     157.500    13.742145     5.833694     3.126462     0.834025     0.440671     0.202307     0.201320     0.121356     0.099403
     135.000    13.859580     7.060907     4.411537     0.600332     0.286087     0.176014     0.122640     0.072078     0.058595
     112.500    10.950127     6.609044     2.746896     0.453414     0.203467     0.120983     0.082450     0.047145     0.038006
      90.000    10.051936     5.992166     1.390020     0.471555     0.260770     0.171313     0.123934     0.075091     0.062561
      67.500     9.653806    12.129735     1.291393     0.334656     0.170340     0.106544     0.074749     0.044229     0.036053
      45.000     7.994519     7.084993     1.094075     0.293956     0.150969     0.095511     0.067500     0.040219     0.032804
      22.500     7.317917     4.090583     1.113160     0.320329     0.166360     0.106651     0.075442     0.045020     0.036807
       0.000     7.237961     6.327664     1.173295     0.366635     0.195192     0.126461     0.090776     0.055165     0.045356

                                                    - GRID SYSTEM RECEPTORS -
                                                  - X AXIS (RANGE    , METERS) -
                 9000.000     10000.000    15000.000     20000.000    30000.000     50000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                            -  CONCENTRATION  -
          -------------------------------------------------------------------------------------------------------------------------
     337.500     0.027314     0.023325     0.012840     0.008510     0.004870     0.002472
     315.000     0.035966     0.029137     0.016248     0.010540     0.006220     0.003160
     292.500     0.027987     0.025562     0.014945     0.009293     0.005298     0.002677
     270.000     0.045435     0.039096     0.022097     0.014747     0.008513     0.004390
     247.500     0.032099     0.027282     0.014797     0.009714     0.005498     0.002760
     225.000     0.056130     0.048171     0.026880     0.018035     0.010405     0.005331
     202.500     0.094373     0.081684     0.047580     0.032109     0.018646     0.009620
     180.000     0.061349     0.052131     0.028244     0.019611     0.010541     0.005308
     157.500     0.043567     0.071520     0.039616     0.024369     0.015115     0.007603
     135.000     0.044887     0.031609     0.022682     0.014984     0.008500     0.004291
     112.500     0.031506     0.020676     0.014311     0.009378     0.005302     0.002670
      90.000     0.052777     0.045323     0.025366     0.017030     0.009858     0.005067
      67.500     0.030145     0.025704     0.014092     0.009346     0.005344     0.002710
      45.000     0.027873     0.023463     0.012889     0.008540     0.004875     0.002470
      22.500     0.030030     0.020309     0.014514     0.009648     0.005527     0.002813
       0.000     0.035175     0.032733     0.018284     0.012294     0.007046     0.003611
```

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Table B-3. Industrial source complex long-term modeling results for case study underground uranium mines (Mine 11), modeled with actual vent orientation

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**** ISCLT ************ Mine 11 With Vertical and Horizontal Vents                                              ******** PAGE     3 ****

                                                    - SOURCE INPUT DATA -

C T SOURCE SOURCE      X          Y       EMISSION  BASE /
A A NUMBER  TYPE   COORDINATE COORDINATE  HEIGHT   ELEV- /                 - SOURCE DETAILS DEPENDING ON TYPE -
R P                    (M)        (M)       (M)    ATION /
D E                                                 (M)  /
--------------------------------------------------------------------------------------------------------------------------------
X       1  STACK     -20.00    -130.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 11.70,
                                                         STACK DIAMETER (M)= 3.000, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   2.42000E+02  2.42000E+02
WARNING - DISTANCE BETWEEN SOURCE         1 AND POINT X,Y=      200.00,      180.00 IS LESS THAN PERMITTED
WARNING - DISTANCE BETWEEN SOURCE         1 AND POINT X,Y=      200.00,      202.50 IS LESS THAN PERMITTED
X       2  STACK     330.00    -160.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)=  9.10,
                                                         STACK DIAMETER (M)= 3.000, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   2.47000E+02  2.47000E+02
X       3  STACK    -240.00     210.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 10.00,
                                                         STACK DIAMETER (M)= 3.000, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   5.45000E+02  5.45000E+02
X       4  STACK     -20.00    -360.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 32.00,
                                                         STACK DIAMETER (M)= 3.500, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   7.45000E+02  7.45000E+02
X       5  STACK   -1010.00    -580.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)=  5.70,
                                                         STACK DIAMETER (M)= 3.500, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   4.04000E+02  3.35000E+02
X       6  STACK     310.00    -950.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 27.30,
                                                         STACK DIAMETER (M)= 3.500, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   3.05000E+02  3.05000E+02
X       7  STACK    -760.00   -1030.00     1.00     0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)=  9.40,
                                                         STACK DIAMETER (M)= 3.500, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                         ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                               - SOURCE STRENGTHS (     CURIES PER YEAR                  ) -
                                                                      SEASON 1      SEASON 2      SEASON 3      SEASON 4
                                                                   8.70000E+01  8.70000E+01
```

Table B-3 (cont.)

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**** ISCLT *************  Mine 11 With Vertical and Horizontal Vents                                        ******** PAGE      4 ****

                                               - SOURCE INPUT DATA (CONT.) -
C T SOURCE SOURCE      X            Y        EMISSION  BASE /
A A NUMBER  TYPE   COORDINATE   COORDINATE   HEIGHT   ELEV- /
R P                   (M)          (M)         (M)    ATION /                 - SOURCE DETAILS DEPENDING ON TYPE -
D E                                                    (M)  /
---------------------------------------------------------------------------------------------------------------------------
X        8  STACK       650.00       140.00    1.00      0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 33.30,
                                                              STACK DIAMETER (M)= 3.500, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                              ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (    CURIES PER YEAR                          ) -
                                                                       SEASON 1     SEASON 2      SEASON 3      SEASON 4
                                                                    4.04000E+02  4.04000E+02
X       10  STACK       450.00      -500.00    1.00      0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)=  9.90,
                                                              STACK DIAMETER (M)= 4.000, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                              ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (    CURIES PER YEAR                          ) -
                                                                       SEASON 1     SEASON 2      SEASON 3      SEASON 4
                                                                    3.20000E+02  3.20000E+02
X       12  AREA        360.00       290.00    1.00      0.00 WIDTH OF AREA (M)=    4.00
                                                                  - SOURCE STRENGTHS (PER CURIES PER YEAR SQUARE METER         ) -
                                                                       SEASON 1     SEASON 2      SEASON 3      SEASON 4
WARNING - DISTANCE BETWEEN SOURCE      12 AND POINT X,Y=     500.00,        45.00 IS LESS THAN PERMITTED
X       13  AREA       -140.00       440.00    1.00      0.00 WIDTH OF AREA (M)=    4.00
                                                                  - SOURCE STRENGTHS (PER CURIES PER YEAR SQUARE METER         ) -
                                                                       SEASON 1     SEASON 2      SEASON 3      SEASON 4
                                                                    1.73000E+01  1.73000E+01
WARNING - DISTANCE BETWEEN SOURCE      13 AND POINT X,Y=     500.00,       337.50 IS LESS THAN PERMITTED
X       14  STACK       730.00      -800.00    1.00      0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 18.70,
                                                              STACK DIAMETER (M)= 2.500, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                              ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (    CURIES PER YEAR                          ) -
                                                                       SEASON 1     SEASON 2      SEASON 3      SEASON 4
                                                                    2.99000E+02  2.99000E+02
WARNING - DISTANCE BETWEEN SOURCE      14 AND POINT X,Y=    1000.00,       135.00 IS LESS THAN PERMITTED
X       15  AREA        580.00      1960.00    1.00      0.00 WIDTH OF AREA (M)=    5.00
                                                                  - SOURCE STRENGTHS (PER CURIES PER YEAR SQUARE METER         ) -
                                                                       SEASON 1     SEASON 2      SEASON 3      SEASON 4
                                                                    2.22000E+00  2.22000E+00
```

Table B-3 (cont.)

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**** ISCLT *************  Mine II With Vertical and Horizontal Vents                                              ********* PAGE     5 ****

      **   ANNUAL GROUND LEVEL CONCENTRATION ( PICO CURIES PER LITER                        ) FROM ALL SOURCES COMBINED          **
                                                              - GRID SYSTEM RECEPTORS -
                                                            - X AXIS (RANGE     , METERS) -
                    200.000        500.000       1000.000       2000.000       3000.000       4000.000       5000.000       7000.000       8000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                                   -  CONCENTRATION  -
                 ---------------------------------------------------------------------------------------------------------------------------------

        337.500       1.870961       0.433468       0.330289       0.105484       0.057997       0.039411       0.029449       0.019132       0.016162
        315.000       1.264934       1.028570       0.249430       0.093995       0.057202       0.040991       0.031006       0.021795       0.018722
        292.500       1.005350       0.629947       0.265614       0.091883       0.055351       0.039200       0.030124       0.020109       0.017110
        270.000       0.837621       0.474777       0.190153       0.087283       0.060004       0.046009       0.037228       0.020603       0.023150
        247.500       0.743569       0.462768       0.206826       0.072297       0.048185       0.035821       0.028179       0.019383       0.016649
        225.000       0.707469       0.460233       0.263638       0.115942       0.076637       0.057311       0.045450       0.031793       0.027516
        202.500       0.811165       0.510650       0.305579       0.166384       0.114122       0.089274       0.073108       0.053165       0.046590
        180.000       0.993256       0.664911       0.323885       0.149472       0.101053       0.073660       0.057353       0.038972       0.033340
        157.500       1.252418       0.715014       0.302072       0.166451       0.116439       0.089582       0.072334       0.051302       0.040904
        135.000       1.613156       0.707715       0.420421       0.163800       0.095335       0.066896       0.051152       0.034110       0.029027
        112.500       2.118837       1.201896       0.414239       0.133090       0.074519       0.050192       0.037242       0.023914       0.020075
         90.000       2.739959       2.549021       0.356436       0.155427       0.097047       0.070142       0.054509       0.037212       0.031093
         67.500       2.991840       7.218555       0.651119       0.137269       0.070875       0.047980       0.035032       0.022946       0.019273
         45.000       2.320549       0.396828       0.500688       0.121574       0.066405       0.042311       0.031255       0.020219       0.017046
         22.500       1.775768       2.521598       0.533386       0.304089       0.078017       0.049658       0.036618       0.023658       0.019939
          0.000       2.012772       2.192571       0.406545       0.159833       0.080395       0.054456       0.041301       0.027456       0.023357

                                                              - GRID SYSTEM RECEPTORS -
                                                            - X AXIS (RANGE     , METERS) -
                   9000.000      10000.000      15000.000      20000.000      30000.000      50000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                                   -  CONCENTRATION  -
                 ---------------------------------------------------------------------------------------------------------------------------------

        337.500       0.013935       0.012204       0.007350       0.005135       0.003123       0.001680
        315.000       0.016351       0.014466       0.008976       0.006363       0.003921       0.002130
        292.500       0.014941       0.013055       0.007956       0.005585       0.003408       0.001835
        270.000       0.020822       0.018222       0.011602       0.008330       0.005207       0.002863
        247.500       0.014531       0.012852       0.007944       0.005606       0.003437       0.001855
        225.000       0.024180       0.021515       0.013626       0.009791       0.006132       0.003391
        202.500       0.041332       0.037061       0.023986       0.017420       0.011023       0.006147
        180.000       0.029000       0.025569       0.015645       0.010994       0.006698       0.003601
        157.500       0.037130       0.034805       0.021870       0.015569       0.009614       0.005220
        135.000       0.025148       0.022103       0.013375       0.009356       0.005667       0.003026
        112.500       0.017198       0.018975       0.008806       0.006056       0.003607       0.001902
         90.000       0.027789       0.024536       0.015845       0.010692       0.006517       0.003526
         67.500       0.016580       0.018429       0.008566       0.005936       0.003571       0.001902
         45.000       0.014672       0.012930       0.007674       0.005337       0.003222       0.001720
         22.500       0.017155       0.014995       0.008945       0.006210       0.003740       0.001993
          0.000       0.020246       0.017307       0.010843       0.007619       0.004651       0.002509
```

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Table B-4. Industrial source complex long-term modeling results for case study underground uranium mines (Mine 12), modeled with actual vent orientation

```
**** ISCLT ************ Mine 12 with Vertical and Horizontal Vents                                               ******** PAGE     3 ****

                                                  - SOURCE INPUT DATA -

C T SOURCE SOURCE       X            Y        EMISSION  BASE /
A A NUMBER  TYPE  COORDINATE   COORDINATE   HEIGHT   ELEV- /
R P                   (M)          (M)          (M)    ATION /                 - SOURCE DETAILS DEPENDING ON TYPE -
D E                                                     (M)  /
-------------------------------------------------------------------------------------------------------------------------------
X       1  AREA       130.00      -100.00     0.00      0.00 WIDTH OF AREA (M)=     4.00
                                                                  - SOURCE STRENGTHS (PER CURIES PER YEAR SQUARE METER        ) -
                                                                         SEASON 1       SEASON 2       SEASON 3       SEASON 4
                                                                       4.02000E+01   4.02000E+01
WARNING - DISTANCE BETWEEN SOURCE         1 AND POINT X,Y=      200.00,      112.50 IS LESS THAN PERMITTED
WARNING - DISTANCE BETWEEN SOURCE         1 AND POINT X,Y=      200.00,      135.00 IS LESS THAN PERMITTED
X       3  AREA       250.00      -100.00     0.00      0.00 WIDTH OF AREA (M)=     4.00
                                                                  - SOURCE STRENGTHS (PER CURIES PER YEAR SQUARE METER        ) -
                                                                         SEASON 1       SEASON 2       SEASON 3       SEASON 4
                                                                       5.07000E+01   5.07000E+01
WARNING - DISTANCE BETWEEN SOURCE         3 AND POINT X,Y=      200.00,      112.50 IS LESS THAN PERMITTED
X       5  STACK      -20.00      -770.00     1.00      0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 19.00,
                                                             STACK DIAMETER (M)= 5.000, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (      CURIES PER YEAR                   ) -
                                                                         SEASON 1       SEASON 2       SEASON 3       SEASON 4
                                                                       5.44000E+02   5.44000E+02
X       6  STACK      -90.00      -250.00     1.00      0.00 GAS EXIT TEMP (DEG K)= 284.20, GAS EXIT VEL. (M/SEC)= 18.00,
                                                             STACK DIAMETER (M)= 5.000, HEIGHT OF ASSO. BLDG. (M)=  0.00, WIDTH OF
                                                             ASSO. BLDG. (M)=   0.00, WAKE EFFECTS FLAG = 0
                                                                  - SOURCE STRENGTHS (      CURIES PER YEAR                   ) -
                                                                         SEASON 1       SEASON 2       SEASON 3       SEASON 4
                                                                       1.94000E+02   1.94000E+02
WARNING - DISTANCE BETWEEN SOURCE         6 AND POINT X,Y=      200.00,      202.50 IS LESS THAN PERMITTED
```

Table B-4 (cont.)

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**** ISCLT *************  Mine 12 With Vertical and Horizontal Vents                              ******** PAGE     8 ****

   **   ANNUAL GROUND LEVEL CONCENTRATION ( PICO CURIES PER LITER                      ) FROM ALL SOURCES COMBINED          **
                                                   - GRID SYSTEM RECEPTORS -
                                                 - X AXIS (RANGE     , METERS) -
                 200.000      500.000     1000.000     2000.000     3000.000     4000.000     5000.000     7000.000     8000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                               -  CONCENTRATION  -
           ------------------------------------------------------------------------------------------------------------------

    337.500      1.655046     0.522092     0.196995     0.069292     0.037877     0.024861     0.018045     0.011171     0.009263
    315.000      1.329022     0.512456     0.209185     0.079628     0.044829     0.029947     0.021976     0.013790     0.011495
    292.500      1.218672     0.488595     0.179087     0.067399     0.037865     0.025285     0.018572     0.011680     0.009750
    270.000      1.582911     0.633024     0.267708     0.104070     0.058935     0.039446     0.029004     0.018272     0.015256
    247.500      2.046039     0.700978     0.238971     0.079804     0.042539     0.027565     0.019906     0.012294     0.010201
    225.000      2.415821     0.672107     0.309223     0.121518     0.068789     0.044106     0.033911     0.021357     0.017852
    202.500      2.792563     1.383826     0.601318     0.226060     0.125082     0.083931     0.061506     0.038736     0.032397
    180.000      5.809899     2.781348     0.742060     0.194380     0.095524     0.059735     0.042190     0.025374     0.020880
    157.500     10.882059     3.486694     0.786637     0.239152     0.123851     0.079733     0.057394     0.035329     0.029280
    135.000      6.989663     4.999204     0.710311     0.166187     0.080517     0.050010     0.035256     0.021219     0.017452
    112.500      8.981521     2.899929     0.403328     0.099687     0.049430     0.031131     0.022094     0.013360     0.011006
     90.000     12.160922     2.329483     0.572503     0.163145     0.084047     0.054008     0.038012     0.023832     0.019725
     67.500      5.413548     1.303370     0.310490     0.089135     0.045889     0.029411     0.021007     0.012901     0.010600
     45.000      3.318948     1.041130     0.274990     0.082625     0.042773     0.027394     0.019606     0.011946     0.009854
     22.500      2.200561     0.873112     0.209372     0.090903     0.047729     0.030807     0.022154     0.013574     0.011221
      0.000      1.597725     0.581869     0.245876     0.093758     0.052705     0.035184     0.025016     0.016193     0.013407

                                                   - GRID SYSTEM RECEPTORS -
                                                 - X AXIS (RANGE     , METERS) -
                9000.000    10000.000    15000.000    20000.000    30000.000    50000.000
Y AXIS (AZIMUTH BEARING, DEGREES )                               -  CONCENTRATION  -
           ------------------------------------------------------------------------------------------------------------------

    337.500      0.007857     0.006705     0.003902     0.002600     0.001577     0.000830
    315.000      0.009790     0.008484     0.004930     0.003384     0.002016     0.001066
    292.500      0.008310     0.007208     0.004199     0.002803     0.001718     0.000907
    270.000      0.013017     0.011343     0.006617     0.004563     0.002736     0.001455
    247.500      0.008463     0.007492     0.004333     0.002963     0.001760     0.000927
    225.000      0.015247     0.013248     0.007771     0.005390     0.003247     0.001740
    202.500      0.027697     0.024009     0.014135     0.009025     0.005920     0.003183
    180.000      0.017616     0.015198     0.008598     0.005838     0.003436     0.001799
    157.500      0.028943     0.021461     0.012354     0.008439     0.005001     0.002632
    135.000      0.014720     0.012655     0.007163     0.004861     0.002856     0.001490
    112.500      0.009263     0.007978     0.004512     0.003087     0.001782     0.000926
     90.000      0.016719     0.014429     0.008269     0.005693     0.003340     0.001750
     67.500      0.009021     0.007775     0.004437     0.003016     0.001777     0.000931
     45.000      0.008325     0.007164     0.004072     0.002759     0.001621     0.000847
     22.500      0.009175     0.008142     0.004645     0.003168     0.001863     0.000975
      0.000      0.011050     0.009941     0.005756     0.003943     0.002343     0.001236
```

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APPENDIX C

CALCULATIONS ON BULKHEAD EFFECTIVENESS AT VARIOUS AIR REMOVAL RATES

Table C-1. Effectiveness of a bulkhead in reducing radon-222 emissions--with zero percent air removal rate(a)

Day	Radon-222 (pCi/L)	Daily radon-222 decay (Ci)	Daily radon-222 removal (Ci)	Radon decay (%)
1	8900	4.91E-2	0	8
2	16300	1.36E-1	0	23
3	22500	2.09E-1	0	36
4	27700	2.70E-1	0	46
5	32100	3.21E-1	0	55
6	35700	3.63E-1	0	62
7	38700	3.98E-1	0	68
8	41200	4.28E-1	0	74
9	43300	4.53E-1	0	78
10	45100	4.73E-1	0	81
11	46500	4.91E-1	0	84
12	47800	5.05E-1	0	87
13	48800	5.17E-1	0	89
14	49700	5.27E-1	0	91
15	50400	5.35E-1	0	92
16	51000	5.42E-1	0	93
17	51500	5.48E-1	0	94
18	51900	5.53E-1	0	95
19	52200	5.57E-1	0	96
20	52500	5.61E-1	0	97
21	52800	5.63E-1	0	97
22	53000	5.66E-1	0	97
23	53100	5.68E-1	0	98
24	53300	5.70E-1	0	98
25	53400	5.71E-1	0	98
26	53500	5.72E-1	0	98
27	53600	5.73E-1	0	99
28	53600	5.74E-1	0	99
29	53700	5.75E-1	0	99
30	53800	5.75E-1	0	99
31	53800	5.76E-1	0	99
32	53800	5.76E-1	0	99
33	53900	5.76E-1	0	99
34	53900	5.77E-1	0	99
35	53900	5.77E-1	0	99
36	53900	5.77E-1	0	99
37	53900	5.77E-1	0	99
38	53900	5.77E-1	0	99
39	54000	5.77E-1	0	99
40	54000	5.77E-1	0	99

(a)Removal rate: percent of total volume of air in sealed area which is removed per day.

Emanation: 5.78×10^{-1}Ci/day.

Flux rate: 9.29 pCi/ft^2-sec.

Drift size: 14 ft x 10 ft x 15000 ft.

Drift volume:: 2,100,000 ft^3.

Table C-2. Effectiveness of a bulkhead in reducing radon-222 emissions--with 10 percent air removal rate(a)

Day	Radon-222 (pCi/L)	Daily radon-222 decay (Ci)	Daily radon-222 removal (Ci)	Radon decay (%)
1	8480	4.75E-2	2.64E-2	8
2	14900	1.27E-1	7.04E-2	21
3	19700	1.86E-1	1.04E-1	32
4	23400	2.32E-1	1.29E-1	40
5	26200	2.66E-1	1.48E-1	45
6	28200	2.92E-1	1.62E-1	50
7	29800	3.11E-1	1.73E-1	53
8	31000	3.26E-1	1.81E-1	56
9	31900	3.37E-1	1.87E-1	58
10	32600	3.45E-1	1.92E-1	59
11	33100	3.52E-1	1.95E-1	60
12	33500	3.57E-1	1.98E-1	61
13	33800	3.60E-1	2.00E-1	62
14	34000	3.63E-1	2.02E-1	62
15	34200	3.65E-1	2.03E-1	63
16	34300	3.67E-1	2.04E-1	63
17	34400	3.68E-1	2.04E-1	63
18	34500	3.69E-1	2.05E-1	63
19	34500	3.69E-1	2.05E-1	63
20	34600	3.70E-1	2.06E-1	64
21	34600	3.70E-1	2.06E-1	64
22	34600	3.71E-1	2.06E-1	64
23	34700	3.71E-1	2.06E-1	64
24	34700	3.71E-1	2.06E-1	64
25	34700	3.71E-1	2.06E-1	64
26	34700	3.71E-1	2.06E-1	64
27	34700	3.71E-1	2.06E-1	64
28	34700	3.71E-1	2.06E-1	64
29	34700	3.71E-1	2.06E-1	64
30	34700	3.71E-1	2.06E-1	64
31	34700	3.71E-1	2.06E-1	64
32	34700	3.71E-1	2.06E-1	64
33	34700	3.71E-1	2.06E-1	64

(a) Removal rate: percent of total volume of air in sealed area which is removed per day.

Emanation: 5.78×10^{-1} Ci/day.

Flux rate: 9.29 pCi/ft^2-sec.

Drift size: 14 ft x 10 ft x 15000 ft.

Drift volume:: 2,100,000 ft^3.

Table C-3. Effectiveness of a bulkhead in reducing radon-222 emissions--with 20 percent air removal rate(a)

Day	Radon-222 (pCi/L)	Daily radon-222 decay (Ci)	Daily radon-222 removal (Ci)	Radon decay (%)
1	8090	4.60E-2	5.12E-2	7
2	13600	1.18E-1	1.31E-1	20
3	17400	1.67E-1	1.86E-1	28
4	20000	2.01E-1	2.23E-1	34
5	21800	2.24E-1	2.49E-1	38
6	23000	2.40E-1	2.66E-1	41
7	23800	2.50E-1	2.78E-1	43
8	24400	2.58E-1	2.86E-1	44
9	24800	2.63E-1	2.92E-1	45
10	25000	2.66E-1	2.96E-1	46
11	25200	2.69E-1	2.99E-1	46
12	25300	2.70E-1	3.00E-1	46
13	25400	2.71E-1	3.02E-1	46
14	25500	2.72E-1	3.02E-1	47
15	25500	2.73E-1	3.03E-1	47
16	25500	2.73E-1	3.03E-1	47
17	25500	2.73E-1	3.04E-1	47
18	25500	2.73E-1	3.04E-1	47
19	25600	2.74E-1	3.04E-1	47
20	25600	2.74E-1	3.04E-1	47
21	25600	2.74E-1	3.04E-1	47
22	25600	2.74E-1	3.04E-1	47
23	25600	2.74E-1	3.04E-1	47
24	25600	2.74E-1	3.04E-1	47

(a) Removal rate: percent of total volume of air in sealed area which is removed per day.

Emanation: 5.78 x 10^{-1}Ci/day.
Flux rate: 9.29 pCi/ft^2-sec.
Drift size: 14 ft x 10 ft x 15000 ft.
Drift volume:: 2,100,000 ft^3.

Table C-4. Effectiveness of a bulkhead in reducing radon-222 emissions--with 50 percent air removal rate(a)

Day	Radon-222 (pCi/L)	Daily radon-222 decay (Ci)	Daily radon-222 removal (Ci)	Radon decay (%)
1	7060	4.20E-2	1.17E-1	7
2	10600	9.68E-2	2.69E-1	16
3	12400	1.25E-1	3.46E-1	21
4	13400	1.39E-1	3.85E-1	23
5	13800	1.46E-1	4.05E-1	25
6	14100	1.49E-1	4.15E-1	25
7	14200	1.51E-1	4.20E-1	26
8	14200	1.52E-1	4.22E-1	26
9	14200	1.52E-1	4.24E-1	26
10	14300	1.53E-1	4.24E-1	26
11	14300	1.53E-1	4.25E-1	26
12	14300	1.53E-1	4.25E-1	26
13	14300	1.53E-1	4.25E-1	26
14	14300	1.53E-1	4.25E-1	26

(a) Removal rate: percent of total volume of air in sealed area which is removed per day.

Emanation: 5.78×10^{-1}Ci/day.

Flux rate: 9.29 pCi/ft^{2}-sec.

Drift size: 14 ft x 10 ft x 15000 ft.

Drift volume:: 2,100,000 ft^{3}.

APPENDIX D

ESTIMATED COSTS OF BLEEDSTREAM CONTROL WITH ACTIVATED CARBON

Table D-1. Capital costs for radon-222 control in underground uranium mines with activated carbon(a)

	System 1	System 2	System 3
Filter	1,800	1,800	1,800
Carbon adsorber, 1800 pound bed	42,600	42,600	42,600
Carbon adsorber, 150 pound bed (qty)	15,000(2)	7,500(1)	0
Electric heater, 75 kilowatt	500	500	0
Air cooling system 550-ft^2 stainless steel heat exchanger: system 1 and 2 2 tons of refrigerant: system 3	20,000	20,000	51,000
Dehumdifier	0	5,000	0
Blower with motors (qty)	2,000(3)	1,400(2)	700(1)
Automatic radon-222 detector	16,900	16,900	16,900
Total equipment cost	$98,800	$95,700	$113,000
Instrumentation	6,500	6,400	7,800
Piping	5,600	5,200	5,400
Electrical	8,400	8,300	9,000
Foundations	2,100	1,900	2,400
Structural	2,100	1,900	2,400
Sitework	5,300	5,000	6,500
Painting and insulation	1,100	1,000	2,200
Field overhead	8,800	8,500	10,800
Engineering (10 percent)	17,300	16,700	19,800
Freight	2,800	2,800	2,200
Taxes (6 percent)	6,000	5,700	6,800
Spares	8,400	8,300	9,500
Total installation cost	$74,400	$71,700	$84,800
Equipment and installation	$173,200	$167,400	$197,800

(a) Based on 100 cfm for bleedstream vent.

Table D-2. Electrical usage
In annual kilowatt hours based upon three shift operation
260 days per year

System 1	
75 kw heater - 1.1 hours per day	21,500
Three blowers, 6 horsepower total	27,900
Lighting, instrumentation, etc.	20,000
Total	69,400
System 2	
75 kw heater - 1.1 hours per day	21,500
Two blowers, 4 horsepower total	18,600
Lighting, instrumentation, etc.	20,000
Total	60,100
System 3	
2 tons of refrigeration, 24 hours per day	187,200
Blower, 3 horsepower	14,000
Lighting, instrumentation, etc.	20,000
Total	221,200

Table D-3. Annualized costs for radon-222 control in underground uranium mines with activated carbon

	System 1	System 2	System 3
A. Direct operating charges			
1. Electricity at 5 cents per kw	$3,500	$ 3,000	$11,100
2. Replacement carbon at $2.50 per pound	1,100	1,100	900
3. Operating labor			
a. Direct - 390 hours at $9.15	3,600	3,600	3,600
b. Supervision - 20 percent of direct labor	700	700	700
4. Maintenance - 6 percent of capital cost	10,400	10,000	11,900
B. Capital charges			
1. Overhead			
a. Plant - 50 percent of 3 and 4	2,200	2,200	2,200
b. Payroll - 20 percent of 3	700	700	700
2. Fixed costs			
a. Capital recovery, 15 percent, 8 years	38,600	37,300	44,100
b. Taxes and insurance - 5 percent	8,700	8,400	9,900
C. Total	$69,500	$67,000	$85,100

APPENDIX E

POPULATION AROUND SELECTED UNDERGROUND URANIUM MINES IN 1982

Table E-1
Population around selected underground uranium mines (Br84)

Mine	State	Distance from mine (km)					
		0-1/2	0-1	0-2	0-3	0-4	0-5
Sunday	Colo.	0	0	0	0	0	0
King Solomon	Colo.	0	0	0	0	0	0
Velvet	Utah	0	0	0	0	0	0
Tony M	Utah	0	0	0	0	0	0
Hack Canyon	Arizona	1	1	1	1	1	1
Pidgeon	Arizona	0	0	0	0	0	0
Kanab North	Arizona	0	0	0	0	0	0
Dermo-Snyder	Colo./Utah	0	5	21	49	67	83
Wilson-Silverbell	Utah/Colo.	0	0	0	12	20	23
Lisbon	Utah	0	0	0	4	44	44
LaSal	Utah	0	0	53	101	194	194
Hecla	Utah	16	16	20	40	73	73
Big Eagle	Wyoming	0	0	0	0	0	0
Golden Eagle	Wyoming	0	0	0	6	6	6
Sheep Mtn.	Wyoming	0	0	0	0	0	12
Mt. Taylor	New Mexico	0	100	317	336	336	336
Old Church Rock	New Mexico	9	9	70	139	187	364
Church Rock-NE	New Mexico	0	11	22	26	31	31
Church Rock-1	New Mexico	0	11	22	27	31	31
Church Rock-East	New Mexico	0	0	9	57	70	131
Kerr-McGee Sec 30 East	New Mexico	3	3	3	3	3	3
Kerr-McGee Sec 30 West	New Mexico	0	5	5	5	5	6
Kerr-McGee Sec 19	New Mexico	0	0	0	4	4	4
Kerr-McGee Sec 35	New Mexico	0	0	0	0	0	0
Kerr-McGee Sec 36	New Mexico	0	0	0	0	0	0

Table E-1
Population around selected underground uranium mines (Br84) (Continued)

Mine	State	Distance from mine (km)					
		0-1/2	0-1	0-2	0-3	0-4	0-5
Homestake Sec 23	New Mexico	0	0	0	3	3	4
Homestake Sec 25	New Mexico	0	0	0	0	0	0
Nose Rock[(a)]	New Mexico	0	0	0	0	26	35
Mariano Lake	New Mexico	13	44	75	196	274	352
Schwartzwalder[(a)]	Colorado	3	3	63	102	136	147
Totals		42	205	618	1,009	1,375	1,733

(a)The population around this mine is not included in the total because the location is not typical of the industry.

BR84 Bruno G. A., Dirks J. A., Jackson P. O., and Young J. K., U.S. Uranium Mining Industry: Background Information on Economics and Emissions, Pacific Northwest Laboratory, PNL-5035 (UC-2, 11, 51) March 1984.

GLOSSARY

back of drift:	The roof of a drift.
curie (Ci):	A source of radionuclide which undergoes radioactive decay of 3.7×10^{10} disintegrations per second.
cut-and-fill stoping:	A stoping method in which the ore is excavated by successive flat or inclined slices, working upward from the level. After each slice is blasted, all broken ore is removed, and the stope is filled with waste before the next slice is taken out.
Developing stope:	Stope in which development drifts are being driven to gain access to ore.
Drift:	A horizontal opening in or near an ore body and parallel to the course of the vein or the long dimension of the ore body.
drift surface:	Exposed surface of drift.
extracting stope:	Stope in which the ore is being extracted.
haulage drift:	Drift developed for movement of men, supplies, waste, and ore.
HydrEpoxy 300:	Two-component, water-base epoxy manufactured by ACME Chemical & Insulation Company.
half-life of radon:	Time in which a half of radon will decay.
muck:	Ore broken in process of mining.
ore:	Mineral of sufficient value as to quality and quantity which may be mined with profit.
ore body:	Mineral deposit that can be worked at a profit.

orepass:	Vertical or inclined passage for the downward transfer of ore.
picocurie (pCi):	10^{-12} curie; 0.037 disintegration per second.
raise:	Vertical or inclined opening driven upward from a haulage level to the ore level.
reference mine:	The hypothetical mine selected for this study.
ribs of drift:	Side of a pillar or the wall.
room-and-pillar stoping:	Stoping method in which the ore is first mined in rooms and then ore in the pillars is subsequently mined.
shotcrete:	Pneumatically applied portland cement mortar.
slusher:	Mechanical dragshovel loader.
stope:	Unit excavation from which ore is being, or has been, excavated in a series of steps.

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